ISLAMIC UNIVERSITY OF TECHNOLOGY

ORGANISATION OF ISLAMIC COOPERATION

NUMERICAL INVESTIGATION ON HEAT TRANSFER PERFORMANCE USING THERMINOL-55 FLUID IN AN INTERNALLY SIX HEAD RIBBED TUBE

BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING

NOVEMBER 2019

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CERTIFICATE OF RESEARCH

This thesis titled "Numerical Investigation On Heat Transfer Performance Using Therminol-55 Fluid in an Internally Six Head Ribbed Tube" submitted by Mashrur Ertija Shejan (151436) and Sadman Noor (151421) has been accepted as satisfactory in partial fulfillment of the requirement for the Degree of Bachelor of Science in Mechanical Engineering.

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DECLARATION

*I hereby declare that this thesis entitled "***Numerical Investigation On Heat Transfer Performance Using Therminol-55 Fluid in an Internally Six Head Ribbed Tube***" is an authentic report of our study carried out as requirement for the award of degree B.Sc. (Mechanical Engineering) at Islamic University of Technology, Gazipur, Dhaka, under the supervision of Dr. Arafat Ahmed Bhuiyan, MPE, IUT during January 2019 to November 2019.*

The matter embodied in this thesis has not been submitted in part or full to any other institute for award of any degree.

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This is to certify that the above statement made by the students concerned is correct to the best of my knowledge and belief.

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Acknowledgement

We would like to express our sincere thanks to our respected supervisor Dr. Arafat Ahmed Bhuiyan sir for his continuous support and guidance throughout this research period and our undergraduate study. His motivation and advice helped us a lot in every step of this research work and writing of this thesis book. His constructive comments helped us a lot to understand and complete this research work.

We are also grateful to our beloved parents for their continuous encouragement and support.

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NOMENCLATURE

c_p	Specific heat at constant pressure ($Jkg^{-1}\ K^{-1}$)
d_i	Inner diameter of ribbed tube (m)
d_o	Outer diameter of ribbed tube (m)
L	Length of the tube
p	Pitch(m)
e	Depth(m)
w	Width(m)
α	Helix angle
d_h	Hydraulic diameter of the tube (m)
μ	Viscosity (Pa.s)
ρ	Density (kg/m^3)
P	Pressure (Pa)
g	Gravitational Acceleration (m/s^2)
k	Turbulent kinetic energy (m^2/s^2)
h	Convective heat transfer co-efficient ($W/m^2\ k$)
Pr	Prandlt number
Nu	Nusselt number
Q_e	Input heat transfer rate (W)
T	Temperature (K)
u,v,w	Velocity components (m/s)
u_{in}	Inlet velocity (m/s)
x,y,z	Co-ordinate (m)
k_w	Thermal conductivity of wall (W/m K)
k_f	Thermal conductivity of fluid (W/m K)
η	Energy utilization factor

Subscripts

in	Inlet
out	Outlet
f	Fluid
w	Wall

Abstract

For the last several decades, rising energy value and higher material cost coerced researchers all around the world to discover innovative ways of increasing heat transfer performance in all kinds of heat exchangers (HXs). Thermal and hydraulic performance of heat exchanger can be improved in various ways such as change of geometry of the tubes, change of heat transfer fluid etc. In this paper the thermo-hydraulic performance of smooth tube, internally four head ribbed tube has been described and from the analysis of the simulation results a new design of the model has been developed that is internally six head ribbed tube. Through simulation and calculation, the convective heat transfer coefficient and Nusselt number of Therminol 55 in a smooth tube, four head and six head ribbed tube has been determined. Comparison between smooth tube and internally four head and six head ribbed tube has been done which shows that the hast transfer rate of internally four head ribbed tube is increased by 8.2-13.2 percent as compared to the smooth one and heat transfer rate of internally six head ribbed tube is increased by 1.85-2.88 percent as compared to four head ribbed tube. Numerical simulation of three dimensional flow of Therminol 55 heat transfer fluid validates that the heat transfer is improved as the rib valley gives a high heat transfer rate by ribs based on Renormalization group (RNG) k-ε turbulent model in the internally four head ribbed tube.

Keywords: Thermodynamics, fluid mechanics, CFD, swirl dominated flow, Numerical analysis, turbulence, rib, numerical analysis.

Chapter 1

INTRODUCTION

As there is high focus on improving heat exchanger performance and maximizing the efficiency, the energy-oriented industries are trying heart and soul to find ways of achieving these goals in order to minimize cost and reduce their material usage. The techniques of heat transfer enhancement can be classified into two methods- Active method and Passive method. Active methods require external power input for the enhancement of heat transfer incorporating jet impingement, fluid vibration, magnetic field, cams pulsation etc. Passive methods include the geometrical modification of the flow channels by incorporating inserts like ribs, fins, rough surface, baffles etc. Thermal and hydraulic performance of heat exchanger can enhance by using various techniques. Some of the techniques are by- changing the geometry of the heat exchanger pipes, changing the heat transfer fluid, increasing the heat transfer surface area inside pipes, mixing up the fluid flowing through the heat exchanger etc. Among these techniques, changing the geometry of the pipe along with adding additional surface area inside the pipe has been chosen to improve the thermal-hydraulic performance of heat exchanger in this study. The ribbed tube configuration is one of the widely used passive method in industries to enhance the heat transfer in heat exchanger. The thermal performance of smooth tubes in conventional heat exchanger has been found poor because of low convective heat transfer co-efficient of fluid. On the other hand, ribbed tube provides more heat transfer rate based on flow separation and reattachment by the ribs. Again it provides helical flow of the fluid inside the tube results in reduced velocity and thermal boundary layers. This is one of the most viable passive method to increase the performance of heat exchanger and are widely used in various industries and process plants.

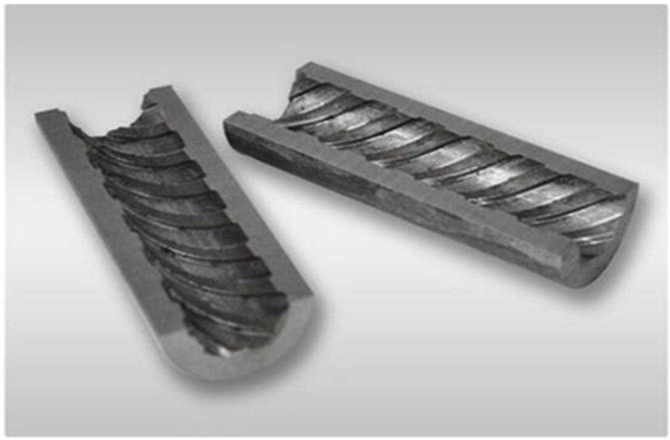

Figure 1.1 internally multi head ribbed tube.

The second most important part is to select the working fluid for heat exchanging between mediums. There are several concerns regarding selection of the fluid. The most important objective is to reduce the pressure drop and keeping the size as small as possible for heat transfer enhancement. Other desirable properties are- high heat transfer rate, low liquid viscosity, high latent heat of vaporization, good wetting capability and high thermal conductivity. It should also be non-corrosive, non-toxic, non-flammable and low cost etc. There are several working fluids such as pressurized water, supercritical CO_2, liquid-water vapor mixtures etc. But they are accompanied by several problems such as low heat transfer rates, higher pressure drop, low thermal conductivity, higher viscosity, limited working temperature range and higher fouling rates etc. Considering all these factors, Therminol-55 synthetic heat transfer fluid can be a suitable fluid that possess more desirable properties and can solve large amount of problems associated with working fluids. Some of the major benefits using Therminol-55 are-

- It provides high performance rate and long life within a large temperature range (200-673) K.
- It has higher resistance to fouling because of less oxidation and solid formation.
- It has excellent low temperature pump ability.

Figure 1.2 Therminol 55 synthetic fluid.

Experimental and numerical simulations of Therminol-55 fluid on friction factor and convective heat transfer co-efficient has been conducted on a single head ribbed tube [1, 2]. Experimental results show that, there is improvement of heat transfer rate in single head ribbed tube compared to the smooth tube. The numerical results show that the heat transfer rate improved in the ribbed tube because of the generation of vortices that is not present in smooth tube. That's why Therminol-55 is an ideal fluid because it has more stability than other heat transfer fluid and possess better properties and can operate in wide temperature range.

The aspect of this work is to investigate the Nusselt number of Therminol-55 by means of convective heat transfer fluid in a four head ribbed tube. The relevant data's and experimental results were taken from the paper of W. Xu [3]. Those data were used to perform the 3-D numerical simulation inside four head ribbed tube to analyze the thermal performance and flow properties of Therminol-55. The numerical simulation was done using ANSYS (Fluent).

Chapter 2

2.1 GOVERNING THEORIES

2.1.1 STEADY FLOW

The term ‘steady’ implies ‘no change of properties at a specific point with time’. For a flow, if the fluid properties at any fixed location does not change with time, this flow is defined to be a steady flow.

2.1.2 TURBULENT FLOW

A fluid flow which is highly disordered and is characterized by velocity fluctuations is called ‘turbulent flow’. Turbulent flows typically occur at high velocities. Since air is a high-viscosity fluid having a dynamic viscosity of 1.895 x 10-5 kg/m-s at 35^{O}C, the flow of Therminol 55 at high velocities results in a turbulent flow.

2.1.3 NO-SLIP CONDITION

The no-slip condition implies that a fluid in direct contact with a surface sticks to the surface and there is no slip. This means that the normal and tangential velocity components of the fluid at the surface is zero. The fluid property responsible for the no-slip condition is viscosity. This phenomenon also gives rise to the boundary layer.

2.1.4 BOUNDARY LAYER THEORY

The boundary layer is a result of the no-slip condition. During flow over a surface, that sticks to the surface slows the adjacent fluid layer because of viscous forces layer between the fluid layers, which slows the next layer, and so on. Hence, when a vertical line is considered on any point on the surface, the fluid velocity is different on every point on the line, up to a certain distance.

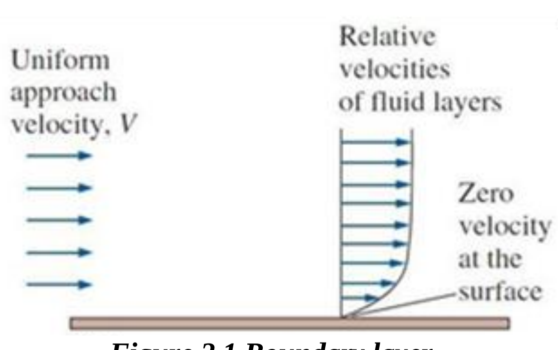

Figure 2.1 Boundary layer.

Because of the no-slip condition, shear friction occurs at the surface which is in contact with the fluid. This friction slows down the moving fluid (inside tube). This drag is known as skin friction drag.

Within the boundary layer region, the viscous effects of the fluid become dominant whereas its influence become less pronounced in the free stream region outside the boundary layer. As such, it is essential to treat the fluid near the surface differently. In numerical simulation it is very important to properly capture this boundary layer to accurately predict the fluid flow and skin friction. This is done by discretizing the flow field, which is discussed in detail in the following sections.

2.2 GOVERNING EQUATIONS

To investigate the effects of rib and the thermal performance of Therminol-55 inside a four head ribbed tube, commercial software ANSYS (Fluent) was used. To simplify the solution, following assumptions were made-

1. The flow of Therminol-55 inside four head ribbed tube is steady.
2. The fluid is incompressible and continuous.
3. The fluid is isotropic and Newtonian fluid.
4. The effect of gravity is negligible.

To investigate the thermal performance and exsmooth the experimental observation in a horizontal test section used in the experiment, three dimensional numerical simulation of Therminol-55 synthetic heat transfer fluid inside a four head ribbed tube were done using ANSYS (Fluent). The modelling involves fundamental mass, momentum and energy equations which are written as follows [4]-

2.2.1 CONTINUITY EQUATION

$$\frac{\partial(\boldsymbol{\rho_f u_k})}{\partial \mathbf{x_k}} = \mathbf{0} \tag{1}$$

2.2.2 MOMENTUM EQUATION

$$\frac{\partial(\rho_f u_i u_k)}{\partial x_i} = -\frac{\partial p}{\partial x_k} + \frac{\partial}{\partial x_i}\left[(\mu_f + \mu_t)\left(\frac{\partial u_i}{\partial x_k} + \frac{\partial u_k}{\partial x_i}\right)\right] + \rho_f g_k \tag{2}$$

Where p is the fluid pressure and μ_f and μ_t are the dynamic and turbulent viscosities respectively of the working fluid.

2.2.3 ENERGY EQUATION

$$\frac{\partial}{\partial x_k}[u_i(\rho_f E_f + p)] = \frac{\partial}{\partial x_k}\left[\left(k_f + \frac{c_p \mu_t}{Pr_t}\right)\frac{\partial T_f}{\partial x_k}\right] \tag{3}$$

Where, ρ_f is the density, k_f is the thermal conductivity and c_p is the heat capacity of the working fluid (Therminol-55). These properties are calculated as a function of fluid temperature T_f. Here E_f is the total internal energy of the Therminol-55 heat transfer fluid.

In solid regions of the wall, the thermal conductivity of the ribbed tube is determined by Fourier's law of heat conduction, which is given by-

$$\boldsymbol{k_w = 0.01566 + [1 + 0.00074(T_w - 273)]} \tag{4}$$

Here $\mathbf{T_w}$ is the wall temperature of the ribbed tube.

The investigation of flow of Therminol 55 through a tube represents certain unique features in its physics and its behavior along with the fundamental flow characteristics. This chapter provides a comprehensive insight into these theories and how they might influence the behavior of flow for the various design of tubes.

Chapter 3

3.1 MODELLING

The geometry of the models has been created using SOLIDWORKS 2016 software.

3.1.1 SMOOTH TUBE

The geometry of the smooth tube has been modeled in a way so that the inner flow region of the tube and the outer surface area of the tube are same as the four head ribbed tube's flow region and outer surface area. The schematic diagram is shown in Figure 3.4, 3.5 and 3.6.

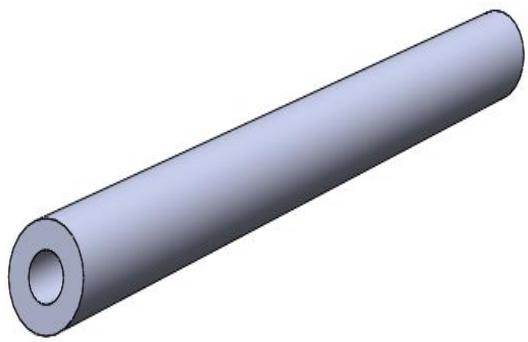

Figure 3.1 Isometric view.

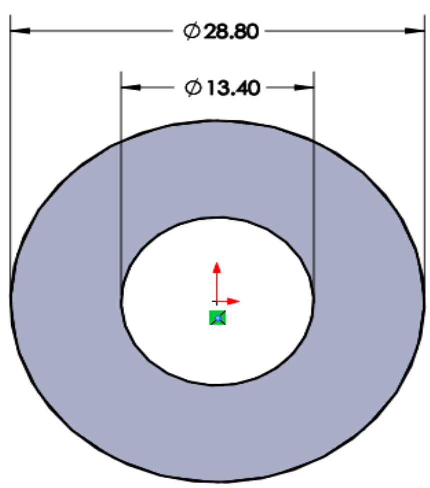

Figure 3.2 Front cut section view.

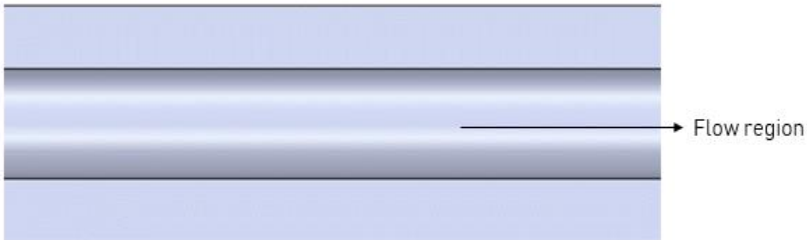

Figure 3.3 Axial cut section view.

The outer diameter (d_o) of the smooth tube is the same as four head ribbed tube in order to keep the outer surface area of the smooth tube same as the four head ribbed tube as the length of both tubes are same. The inner diameter (d_i) of the tube is 13.40mm that allows the flow region of the smooth tube to be same as the four head ribbed tube's flow region.

3.1.2 FOUR HEAD RIBBED TUBE

The dimensions of four head ribbed tube are taken as per experimental setup [3]. The schematic diagram is shown in Figure 3.1, 3.2 and 3.3.

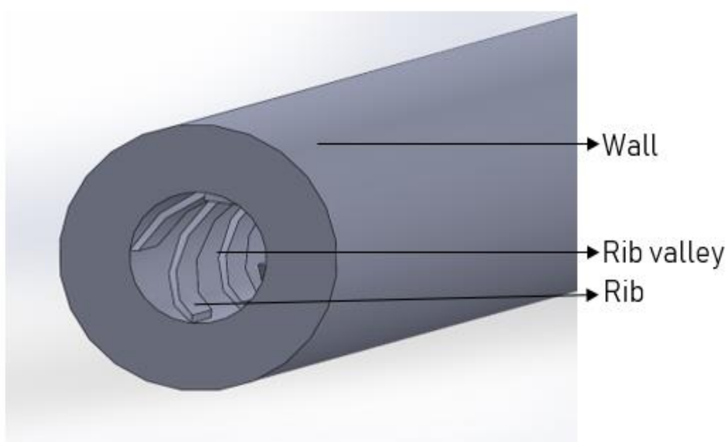

Figure 3.4 Isometric view.

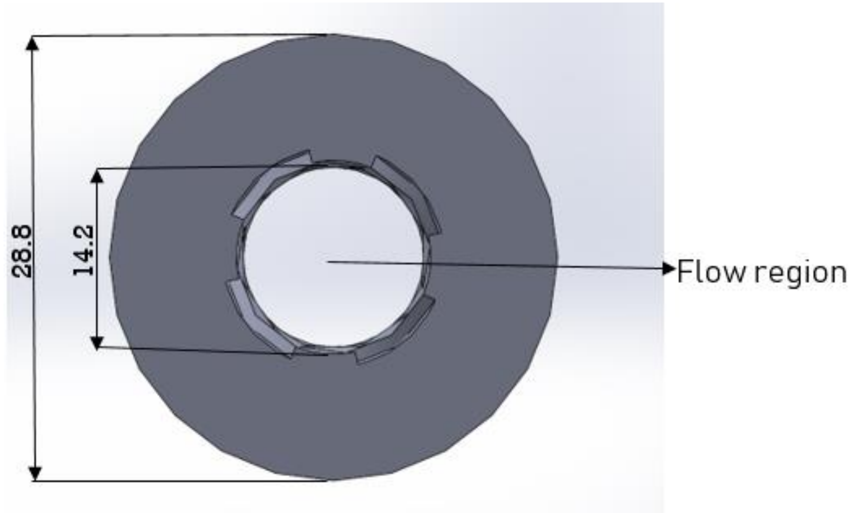

Figure 3.5 Front cut section view.

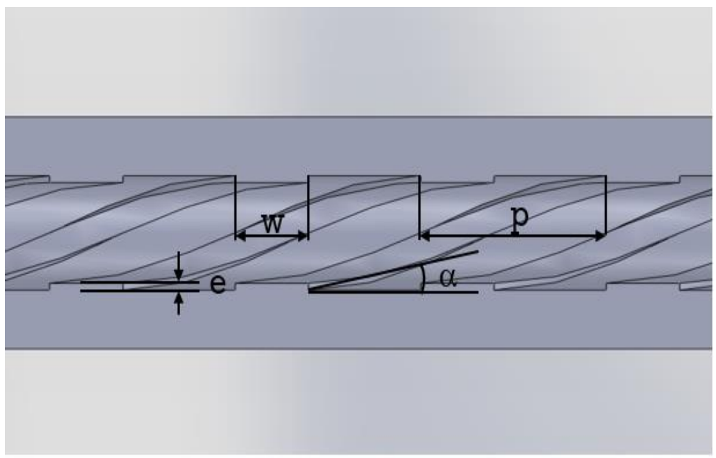

Figure 3.6 Axial cut section view.

The inner diameter(d_i) of the ribbed tube is 14.2mm and the outer diameter(d_o) is 28.8mm.The length(L) of the ribbed tube is 2m. The pitch(p) is 21mm and the rib height (e) is 0.85mm. The rib longitudinal width(w) is 8.3mm while the helix angle(α) is 54°. The hydraulic diameter of the ribbed tube is 15.24mm.

3.1.3 SIX HEAD RIBBED TUBE

The geometry of the six head ribbed tube is also determined in a way such that the inner flow region and the tube volume is same as the six head ribbed tube to compare the significance of the tube designs effectively. The schematics of the six head ribbed tube are shown in Figure 3.7, 3.8 and 3.9.

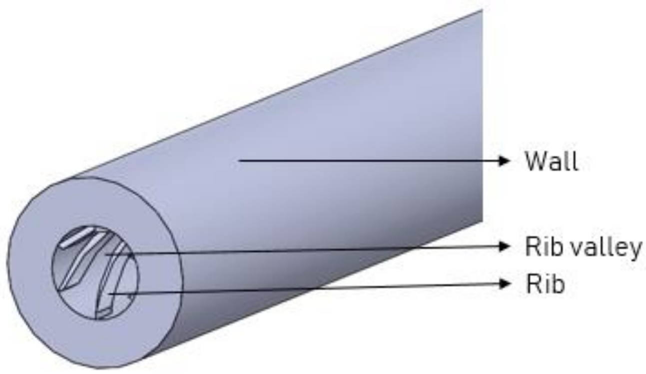

Figure 3.7 Isometric view.

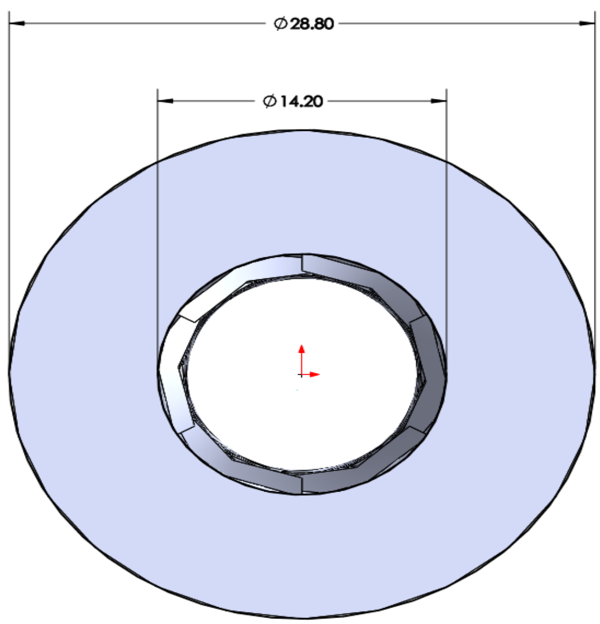

Figure 3.8 Front cut section view.

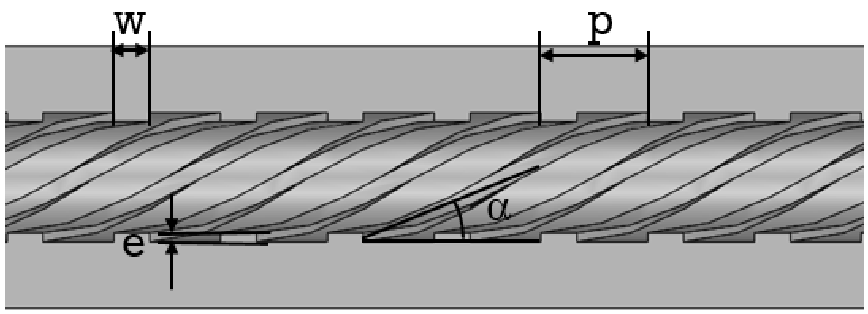

Figure 3.9 Axial cut section view.

The inner diameter(d_i) of the six head ribbed tube is 14.2mm and the outer diameter(d_o) is 28.8mm which are same as the four head ribbed tube.The length(L) of the ribbed tube is also 2m. The pitch(p) is 21mm and the rib height (e) is 1mm. The rib longitudinal width(w) is 4.7033mm while the helix angle(α) is 54°. The hydraulic diameter of the ribbed tube is 15.24mm.

3.2 MESHING

For analyzing the heat transfer in different tube models, geometries were generated with different flow criteria and rib dimensions. These geometries were then imported into ANSYS ICEM and meshed. The meshing parameters are detailed below. ANSYS ICEM was used in this application due to its robust nature and reliability when dealing with complex geometry.

For accurate solutions to be produced, the numerical solution of the differential equations should achieve proper convergence. For this to occur, the mesh, must be of proper quality, as low-quality mesh may result in distortion of the geometry and computational grid, producing inaccurate results.

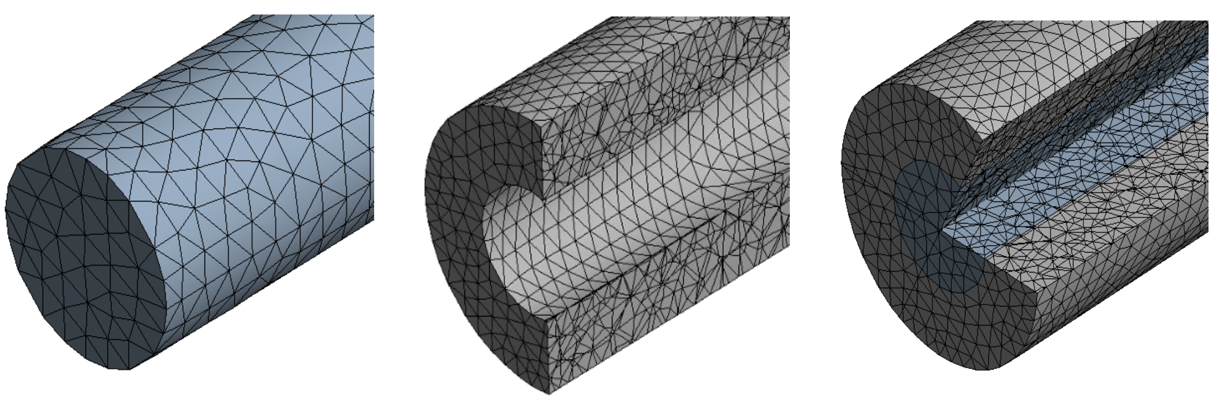

Figure 3.10 Smooth tube's fluid part, solid part and assembly mesh.

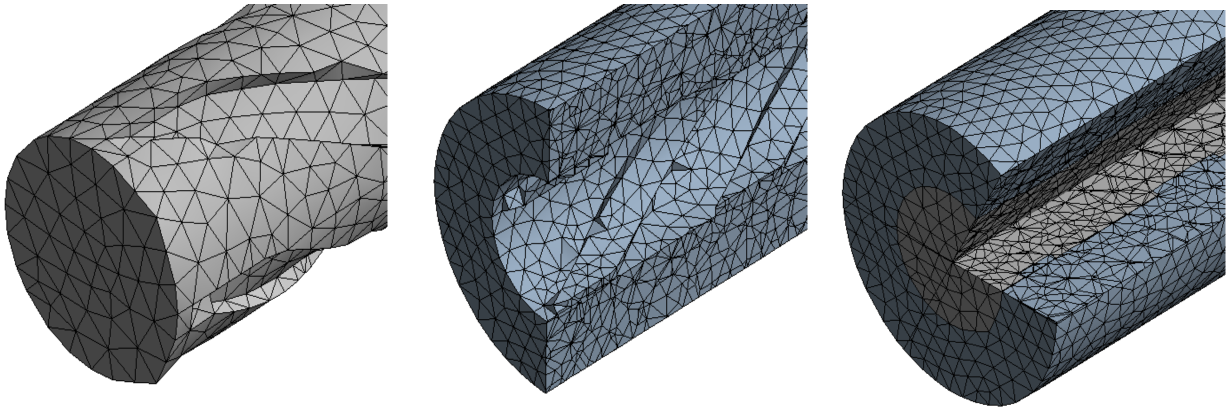

Figure 3.11 Four head ribbed tube's fluid part, solid part and assembly mesh.

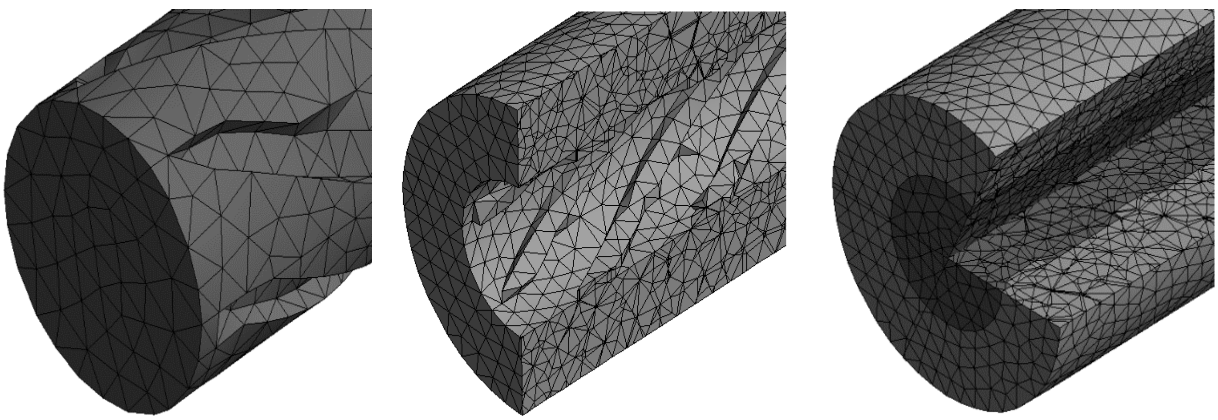

Figure 3.12 Six head ribbed tube's fluid part, solid part and assembly mesh.

The main concern of the study is the heat transfer performance of Therminol 55 in different tube models. So, the interest in this study is the fluid flowing inside the fluid flow region, as well the solid part of tubes. The close region around the inside tube wall was of high interest as this was the region of boundary layer separation, pressure gradients and heat transfer from tube to Therminol 55. As such, high density mesh has been used in this region in order to obtain accurate values for flow parameters.

For better comparison among the tube models the same meshing has been done for all the tubes. Same mesh size has been used for both tube and fluid part, with a prism of 5 layers and expansion factor of 1.2 and also a total count of 186038 nodes and 980232 elements. The assembly mesh method was set to tetrahedrons. The transition was set smooth and special sizing was done at the curvature with high smoothing.

3.2.1 GRID INDEPENDCY TEST

In the grid independence test, three different types of grids ie. Finer, mid and coarse grids having grid numbers 980232,836542,554595 respectively were tested at inlet velocity of 1.80 m/s, temperature 356.7 K and heat flux 3727.6 W. The results are shown in fig x. For finer grids the error percentage is 2.77% approximately whereas for mid and coarse grids, the percentage were about 4.48% and 12.20% respectively. The result accuracy for finer and mid grids were below 5% which is highly acceptable. Since the mid and finer grids have low deviation between their grid numbers, they almost took the same time for the solution. Though finer grids were used for the solution in order to maintain high accuracy and precision of the results.

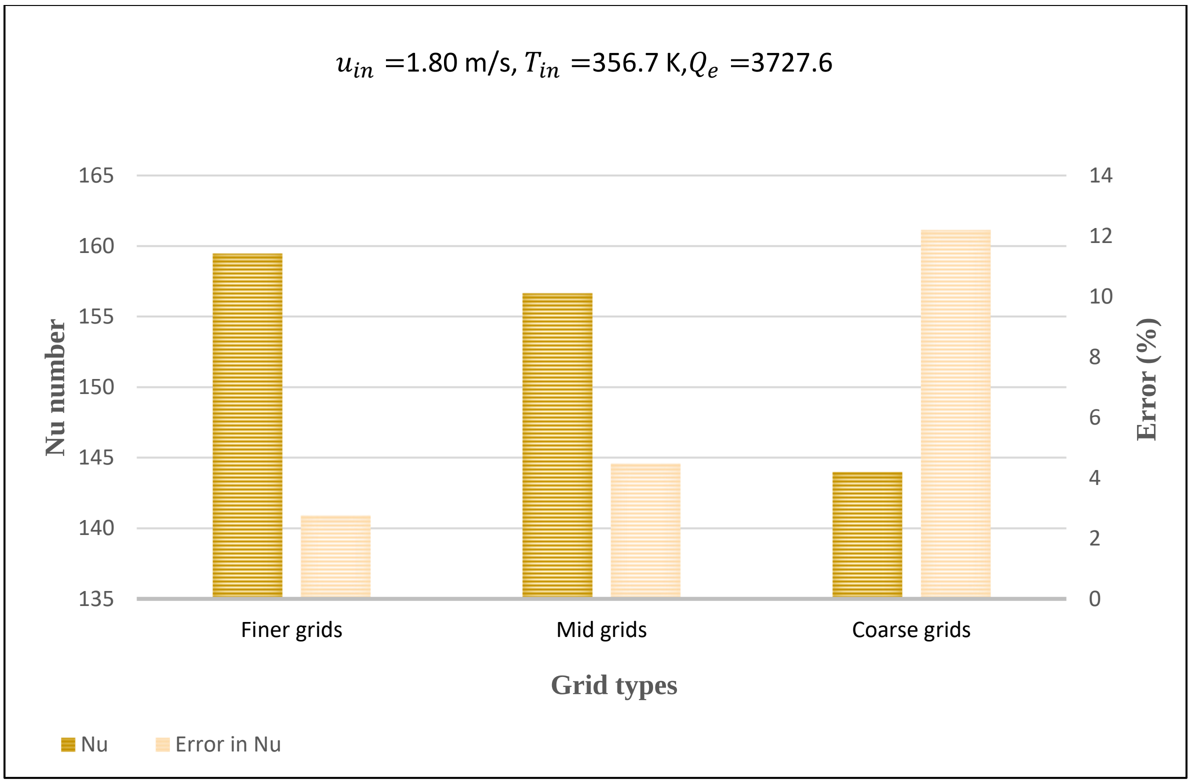

Figure 3.13 Grid independency test of Nu number.

3.3 BOUNDARY CONDITIONS

The boundary conditions for the numerical simulation are specified as-

At the inlet of the ribbed tube, the uniform velocity and temperature profiles are defined as per experimental setup,

$$\boldsymbol{u = v = 0}, \qquad \boldsymbol{w = w_{in}}, \qquad \boldsymbol{T_f = T_{in}} \tag{5}$$

At the outlet of the four head ribbed tube, the flow condition with velocity components and temperature derivatives equal to zero.

At the wall, uniform heat flux condition is applied with velocity components are equal to zero.

$$\boldsymbol{q_w = q_e} \tag{6}$$

The Renormalization group (RNG) Ƙ-Ɛ model is used to solve the turbulent flow problem. The effect of swirl on turbulence is included in the RNG model, enhancing accuracy for swirling flows**[4]**. Enhanced wall treatment is used as the near wall treatment.

The properties of Therminol-55 are incorporated in ANSYS (Fluent) through user defined function(UDF). SIMPLEC scheme is used to solve the pressure-velocity coupling while the second order upwind condition was used to discretize the convective terms. The minimum convergence criteria is set to 10^{-4} for continuity equation, velocity and turbulence quantities and 10^{-8} for energy equation.

Uniform heat flux on the tube wall is emulated for simulation. The wall heat flux is calculated as

$$\boldsymbol{q_e = \frac{Q_e \eta}{\pi d_o L}} \tag{7}$$

Where L is the length of the test section.

The co efficient of energy utilization η is 98%.

The convective heat transfer coefficient of Therminol 55 heat transfer fluid in the tube models is

$$\boldsymbol{h = \frac{Q_e \eta}{(T_w - T_f)\pi d_o L}} \tag{8}$$

Where T_w is a mean wall temperature and T_f is an arithmetic mean temperature of Therminol 55 heat transfer fluid in flow region of the tube models. Here,

$$\boldsymbol{T_f = 0.5(T_{in} + T_{out})} \tag{9}$$

Where, T_{in} and T_{out} are inlet and outlet temperatures respectively.

Nusselt number is defined as follow:

$$\boldsymbol{Nu = \frac{hd_h}{k_f}} \tag{10}$$

Where, h is the convective heat transfer co-efficient and k_f is thermal conductivity of Therminol 55.

3.4 SIMULATION

To determine the optimum geometry of the tube, the thermo-hydraulic performance of Therminol 55 heat transfer fluid is determined by numerical simulation at different rib heights. For simulation ANSYS Fluent has been used to predict heat transfer at different rib pitch and height of the internally four head ribbed tube.

In the simulation it is observed that the Nusselt number is significantly increased as compared to smooth tube for the same geometry. It is because the internal ribs provide increased heat transfer surface area as in finned tube and also enhances convective heat transfer by increasing the mixing of fluid at the ribs, that is caused by flow recirculation. As a result, more turbulence is created in the boundary layer. The ribs also provide swirling effect at the rib vicinity and so the thermal boundary layer of the heat transfer fluid inside the ribs becomes thinner because of flow separation and recirculation. The centrifugal force generated by the swirling effect induces rotational flow and increases the relative velocity between the tube wall and core fluid. As a result, the Nusselt number and heat transfer of Therminol 55 gets increased.

The convergence residuals have been observed and it would never be zero because of error in simulation for many reasons. Therefore, deviation between simulated data and actual may exist.

A number of numerical simulation has been conducted that provides information about the flow and temperature in longitudinal and transverse direction. For simulation different set of boundary condition was set to determine heat transfer coefficients and Nusselt numbers for different inlet values in different tube models. A larger Nusselt number indicates greater heat transfer rate in each models.

Chapter 4

RESULTS

4.1 TEMPERATURE BASED

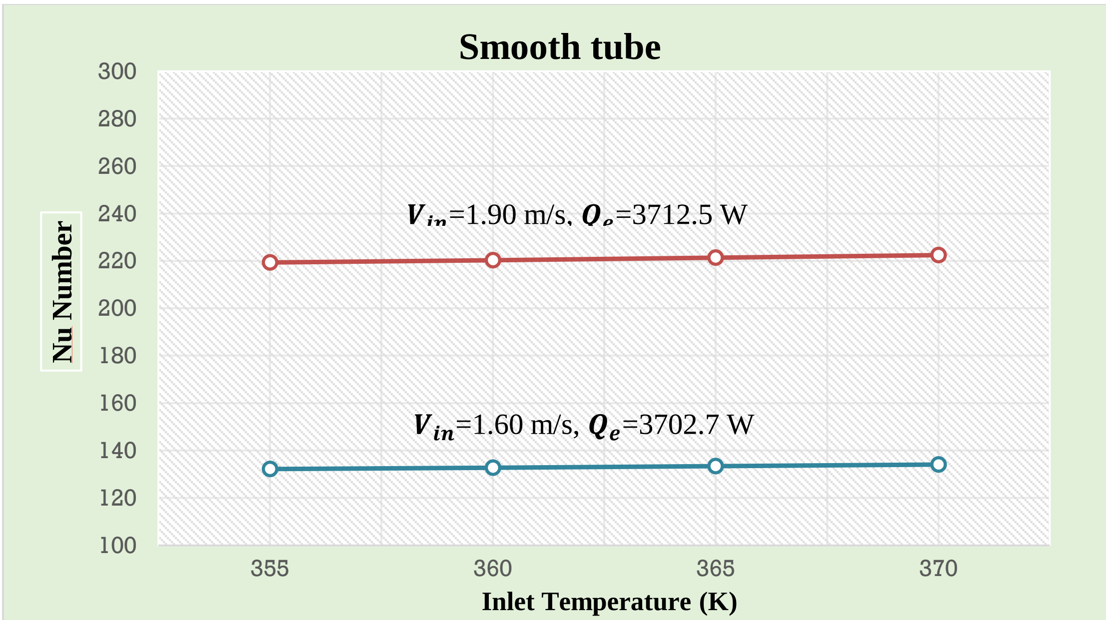

Figure 4.1 Measured Nu numbers at different inlet temperatures in smooth tube.

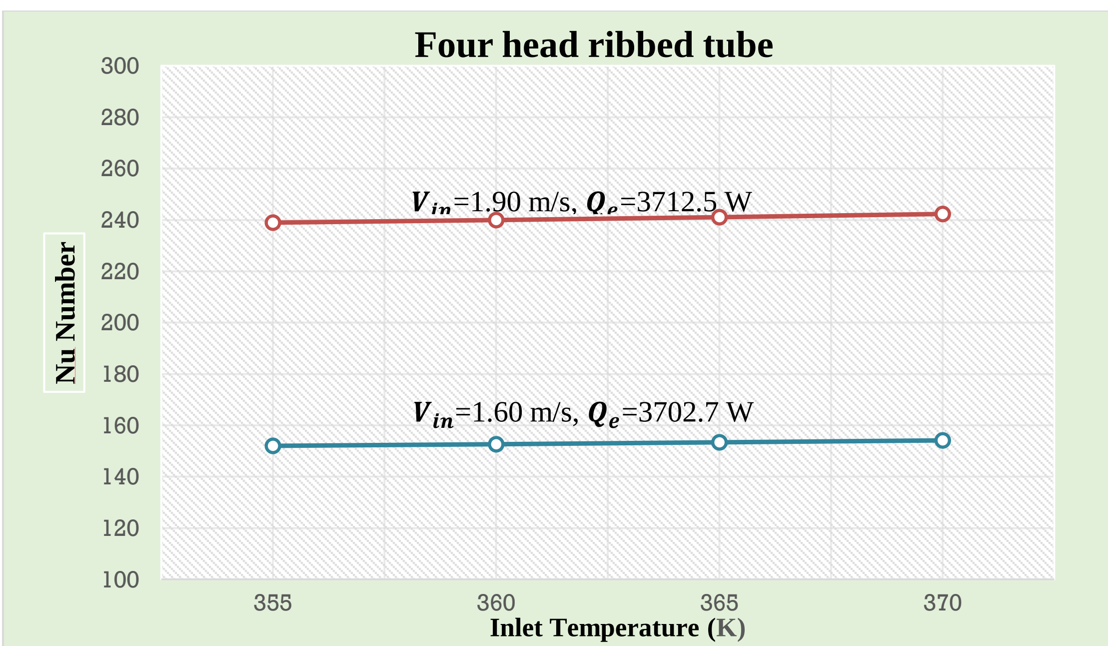

Figure 4.2 Measured Nu numbers at different inlet temperatures in four head ribbed tube.

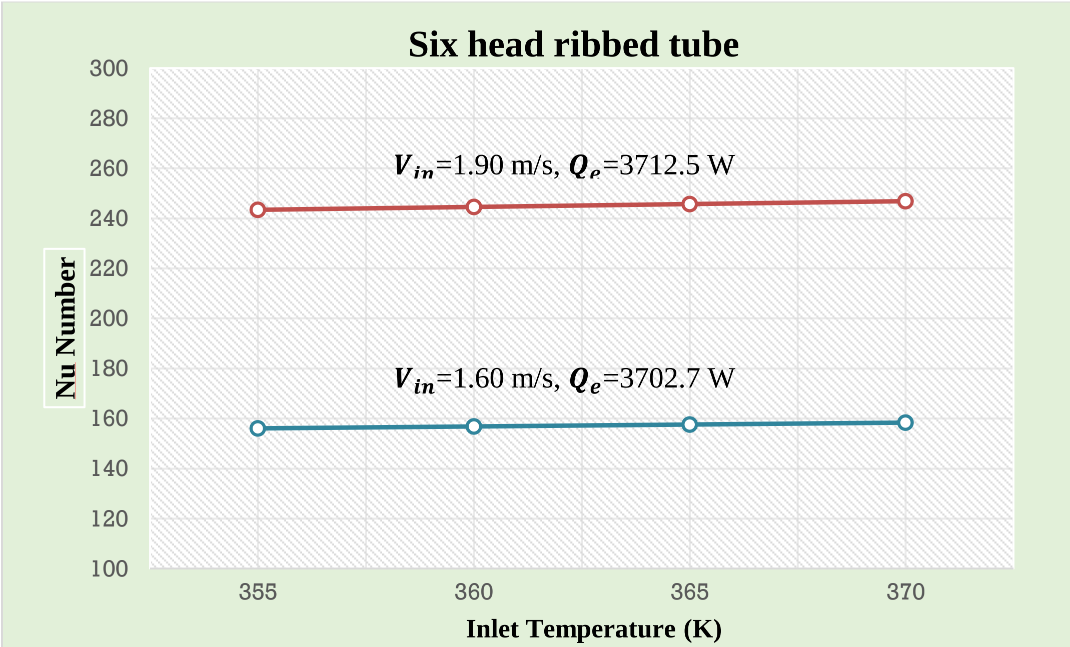

Figure 4.3 Measured Nu number at different inlet temperatures in six head ribbed tube.

In Figure 4.1, 4.2 and 4.3 measured Nusselt number has been shown for smooth tube, four head ribbed tube and six head ribbed tube respectively with respect to different inlet temperatures. In each graph there are two cases in which the inlet velocity of Therminol 55 and the heat flux are kept constant and the points have been calculated for variable inlet temperature of Therminol 55. The blue and red lines represent the two different cases in the simulation of variable temperature.

4.2 VELOCITY BASED

In Figure 4.4, 4.5 and 4.6 measured Nusselt number has been shown for smooth tube, four head ribbed tube and six head ribbed tube respectively. In each graph there are three cases in which the inlet temperature of Therminol 55 and the heat flux are kept constant and the points have been calculated for variable inlet velocity of Therminol 55. The three cases which were considered for simulation are given below,

1st case	2nd case	3rd case
$\boldsymbol{T_{in} = 359.2\ K}$	$T_{in} = 356.7\ K$	$T_{in} = 356.6\ K$
$\boldsymbol{Q_e = 3607.5}$	$Q_e = 3727.6$	$Q_e = 3763.6\ W$

Table 4.1 Temperatures and heat flux in 3 cases.

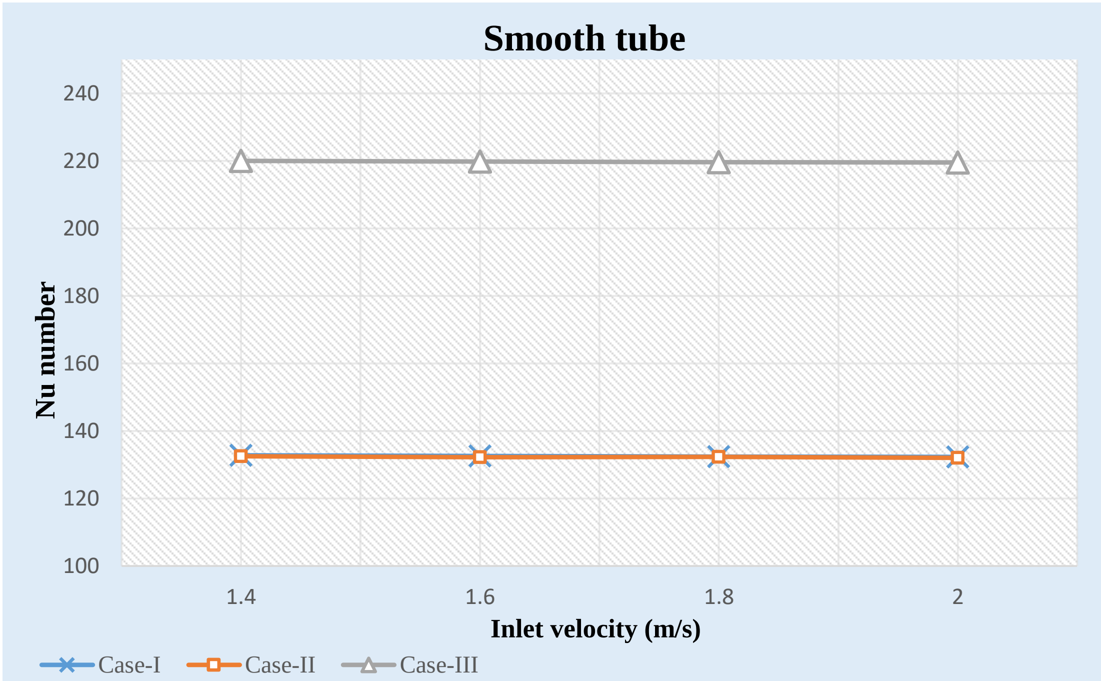

Figure 4.4 Measured Nu number at different inlet velocities in smooth tube.

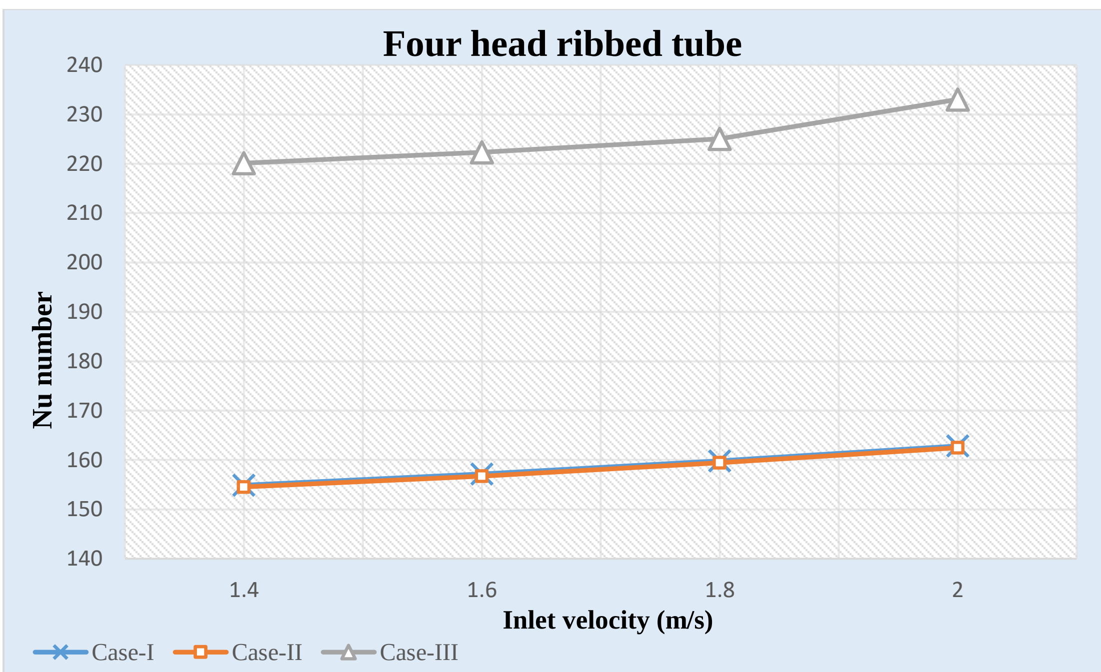

Figure 4.5 Measured Nu number at different inlet velocities in four head ribbed tube.

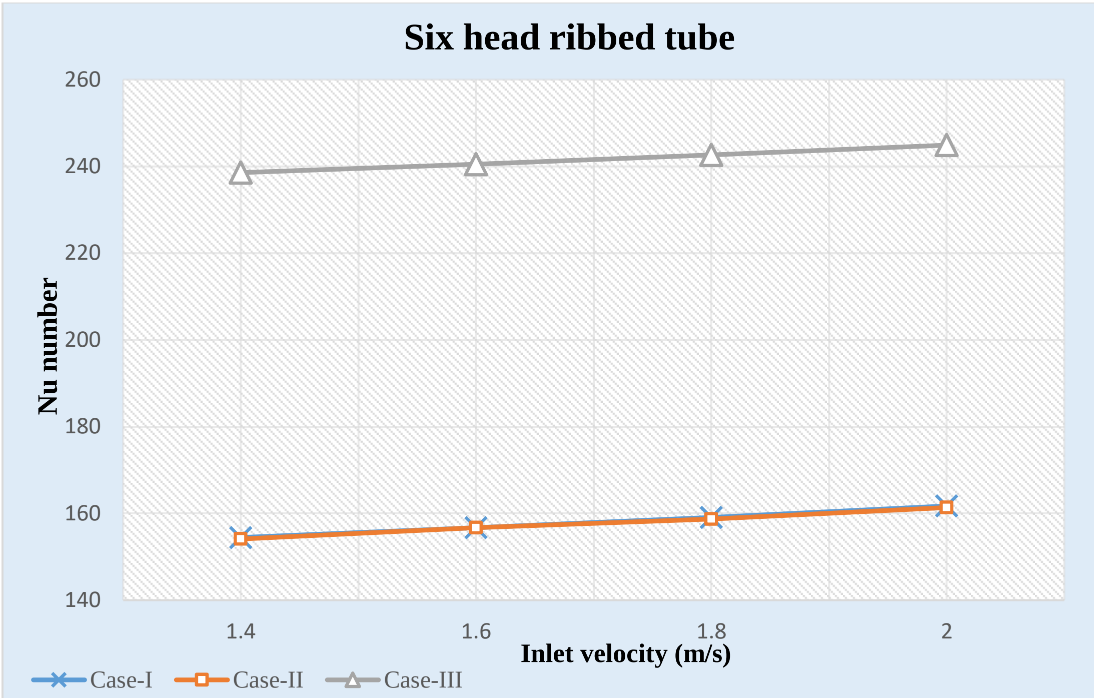

Figure 4.6 Measured Nu number at different inlet velocities in six head ribbed tube.

In Figure 4.4, 4.5 and 4.6 measured Nusselt number has been shown for smooth tube, four head ribbed tube and six head ribbed tube sequentially with respect to different inlet velocities. In each graph there are three cases in which the inlet temperature of Therminol 55 and the heat flux are kept constant and the points have been calculated for variable inlet velocity of Therminol 55. For case 1 and case 2 the measured Nusselt numbers are quite similar at the particular velocities compared to each other but for case 3 the Nusselt number values are massively increased. Analyzing the three graphs it can be noticed that the Nusselt number gradually increased with increasing velocity for flow in four head ribbed tube and six head ribbed tube. It's because, more turbulence is created because of higher inlet velocity. As a result, there is more mixing of fluid inside the flow region which enhances heat transfer from tube wall to the Therminol heat transfer fluid and so Nusselt number is increased. In case of flow in smooth tube the Nusselt number remain quite similar for different inlet velocities in each cases as the flow inside smooth tube is considered to be laminar and it doesn't enhance fluid heat transfer. So increasing the fluid velocity, the Nusselt number is rather decreased for flow inside smooth tube.

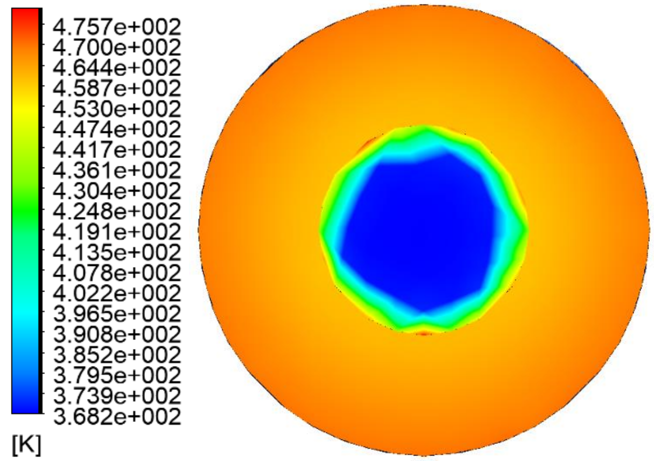

Figure 4.7 Smooth tube temperature contour.

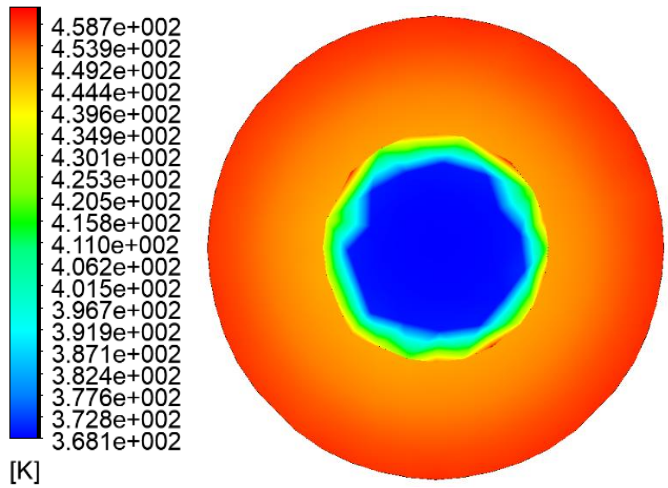

Figure 4.8 Four head ribbed tube temperature contour.

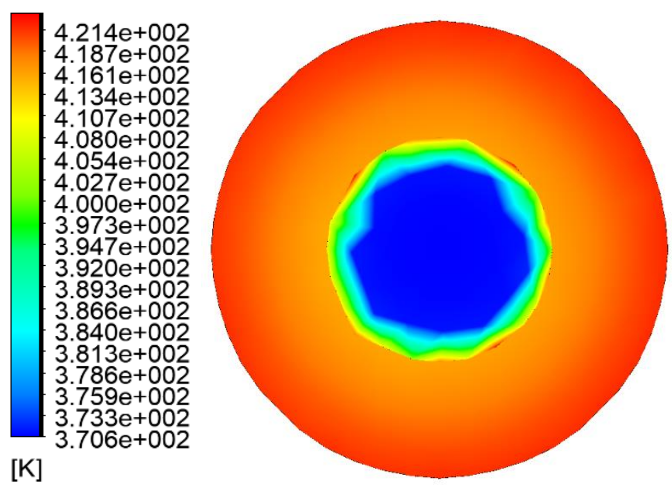

Figure 4.9 Six head ribbed tube temperature contour.

In Figure 4.7, 4.8 and 4.9, temperature contour at the outlet of the three tube models has been shown. Here although the contours look quite similar to each other but their highest and lowest temperature values vary. The core fluid region of all the models have low temperature zone whereas fluid temperature gets risen as it proceeds toward the boundary wall. The thickness of temperature boundary layer is lowest for the smooth tube and it gets higher in four head and six head ribbed tube respectively because of the flow separation and recirculation at the rib vicinity.

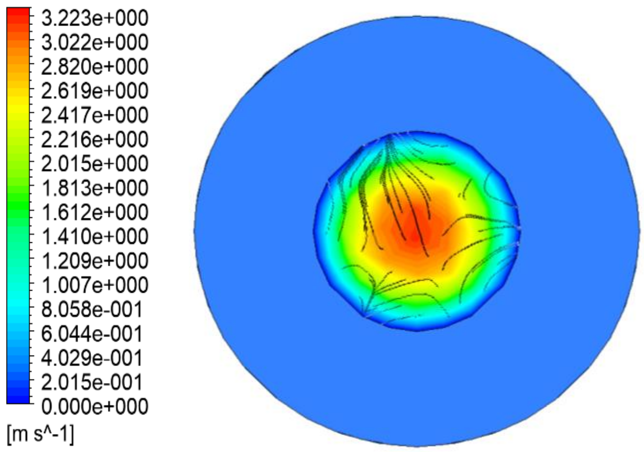

Figure 4.10 Smooth tube velocity contour.

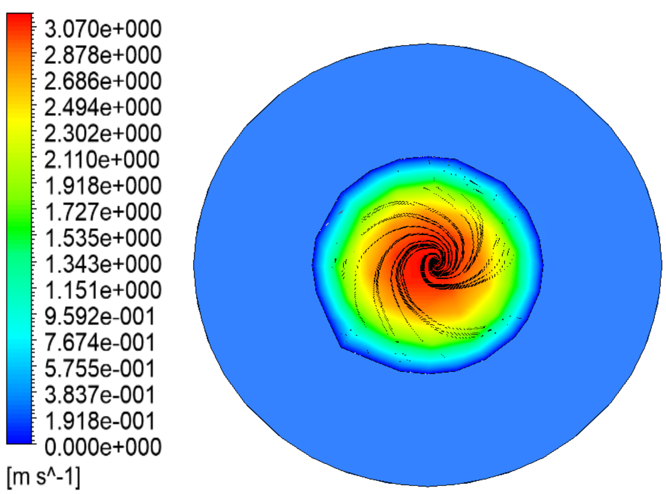

Figure 4.11 Four head ribbed tube velocity contour.

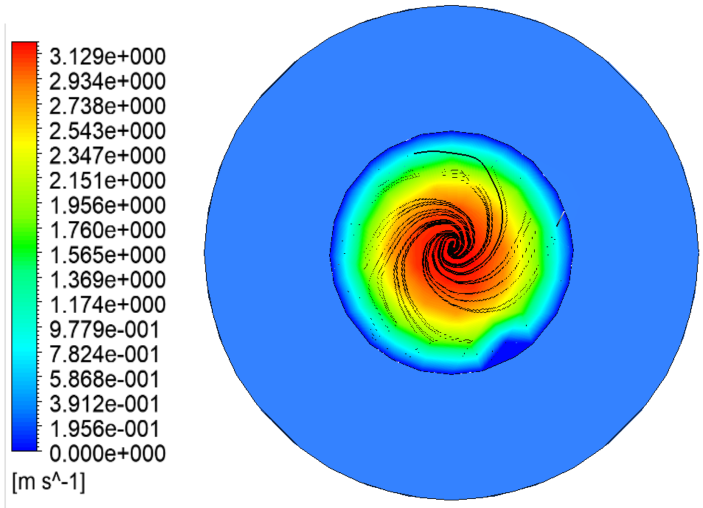

Figure 4.12 Six head ribbed tube velocity contour.

In Figure 4.10, 4.11 and 4.12, temperature contour and streamlines of the fluid at the outlet of the tube models gas been presented. The velocity of the fluid is zero at the inside tube wall because of no slip boundary condition imposed and it gradually increases from the tube wall to the center of the flow region.so, the highest velocity is at the core of the flow region. From the streamlines, it can be visualized that swirling effect is generated at the flow region in the four head and six head ribbed tubes whereas in case of smooth tube there is no swirling effect.

Chapter 5

VALIDATION

Since the paper [3] that has been followed as a reference that worked with the four head ribbed tube, the validation has been done using the values of the results. Xu et al. has conducted an experiment and presented the results in the paper. In that paper, 3 cases has been taken care of, where in each case, heat transfer rate(Q_e) and inlet temperature(T_{in}) are constant. They calculated the Nusselt number(Nu) against variable inlet velocity(v_{in}). Using these initial conditions, numerical calculations are done. The paper firmly shows the comparison of these numerical results against the experimental results earned from the paper of Xu et al.

In the first case, the parameters given are, $\mathbf{Q_e}$= 3607.5W and $\mathbf{T_{in}}$=359.2K. The experimental result shows that, the Nusselt number(Nu) is 147 for inlet velocity $\mathbf{v_{in}}$=1.42 m/s and 150 for inlet velocity $\mathbf{v_{in}}$=1.51 m/s. The numerical solution done by the author almost gets the similar result where the Nu is 154.9016 for v_{in}=1.42 m/s and 155.9744 for v_{in}=1.51 m/s. The percentage of error between experimental and numerical results for this case is 5% for v_{in}=1.42 m/s and 4% for v_{in}=1.51 m/s.

Numerical calculation for other velocities are also done to have the total insight of the deviation of Nusselt number with inlet velocity. The results are shown in the following graph and tabulated value-

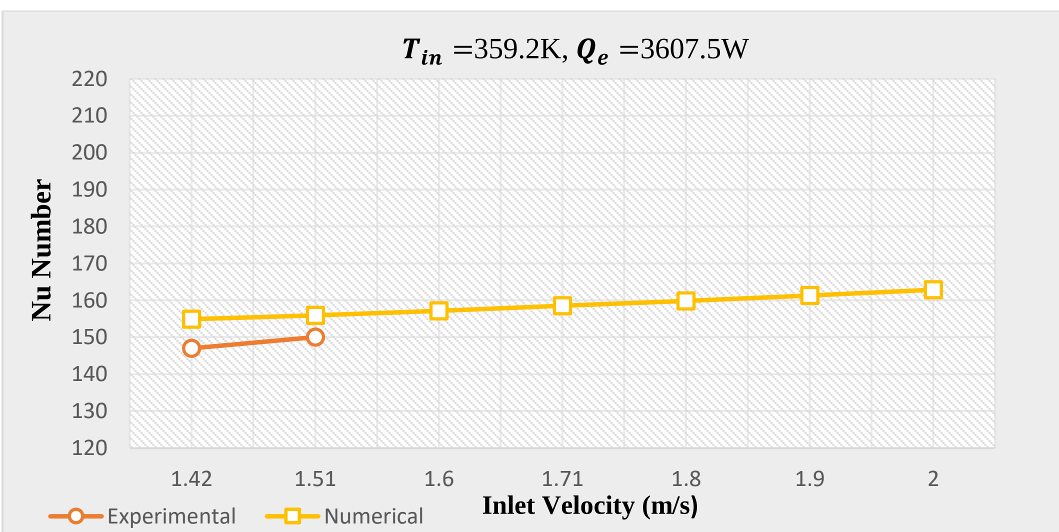

Figure 5.1 Comparison between measured and experimental Nu numbers with respect to different velocities (1st case).

Inlet Velocity (m/s)	Nu (Experimental)	Nu (Numerical)	Percentage of error (%)
1.42	147	154.9016	5%
1.51	150	155.9744	4%
1.60		157.1859	
1.71		158.5589	
1.80		159.8229	
1.90		161.2889	
2.0		162.8531	

Table 5.1 Error between experimental and simulated Nu number (1st case).

In the second case, the heat transfer rate increases and the inlet temperature decreases from the first case as the initial conditions given are, $\mathbf{Q_e}$=3727.6 W and $\mathbf{T_{in}}$=356.7 K. The experimental result shows that, Nusselt number (Nu) is 154 for v_{in}=1.71 m/s and 164 for v_{in}=1.80 m/s. The numerical calculations show that Nu is 158.2014 for v_{in}=1.71 m/s and 159.4548 for v_{in}=1.80 m/s. The percentage of errors between experimental and numerical results for this case are both 3%. Numerical calculations for other velocities are done and the results are shown below-

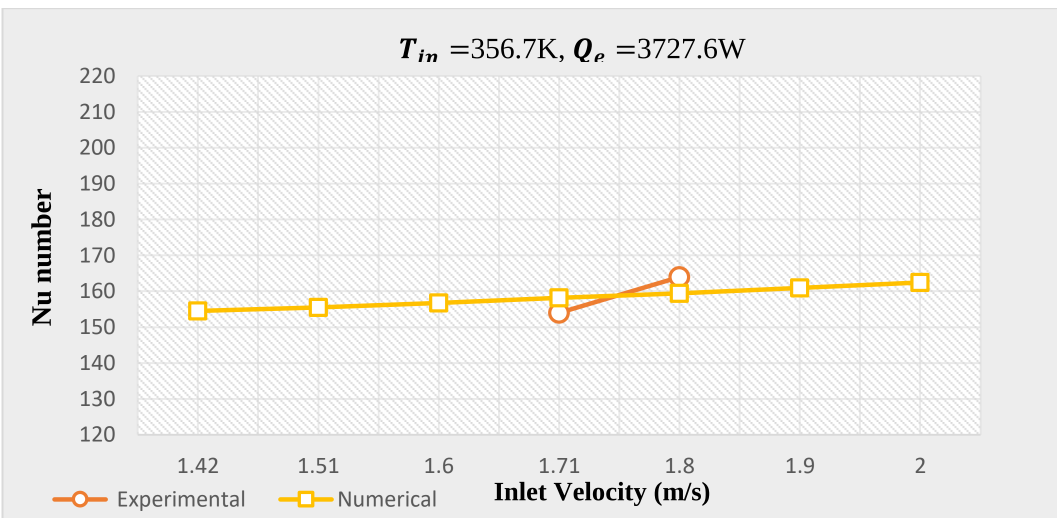

Figure 5.2 Comparison between measured and experimental Nu numbers with respect to different velocities (2nd case).

Inlet Velocity (m/s)	Nu (Experimental)	Nu (Numerical)	Percentage of error (%)
1.42		154.5479	
1.51		155.4590	
1.60		156.7465	
1.71	154	158.2014	3%
1.80	164	159.4548	3%
1.90		160.9266	
2.0		162.4859	

Table 5.2 Error between experimental and simulated Nu number (2nd case).

Finally, in the third case, again the heat transfer rate(Q_e) is increased and the inlet temperature(T_{in}) is decreased from the previous case. The initial conditions are, Q_e= 3763.6 W and T_{in}= 356.6 K. The experimental results show that, Nusselt number(Nu) is 235 for v_{in}=1.9 m/s and 240 for v_{in}=2 m/s. The numerical results show that Nu is 231.5099 for v_{in}=1.9 m/s and 233.0374 for v_{in}=2 m/s which is close the experimental results. The percentage error between experimental and numerical results for this case are 1% for v_{in}=1.9 m/s and 3% for v_{in}=2 m/s. Numerical calculations for other velocities are done and the results are shown below-

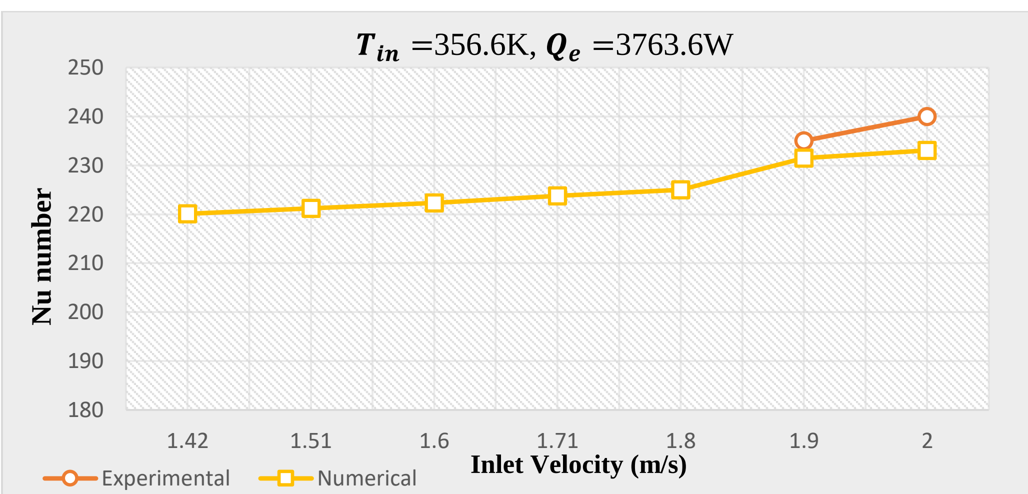

Figure 5.3 Comparison between measured and experimental Nu numbers with respect to different velocities (3rd case).

Inlet Velocity (m/s)	**Nu (Experimental)**	**Nu (Numerical)**	**Percentage of error (%)**
1.42		220.1187	
1.51		221.1944	
1.60		222.3068	
1.71		223.7737	
1.80		225.0344	
1.90	235	231.5099	1%
2.0	240	233.0374	3%

Table 5.3 Error between experimental and simulated Nu number (3rd case).

From all the three cases, it is evident that, the percentage of error between the experimental results and numerical results lies within 5%, which is much appreciable.

Chapter 6

COMPARISON

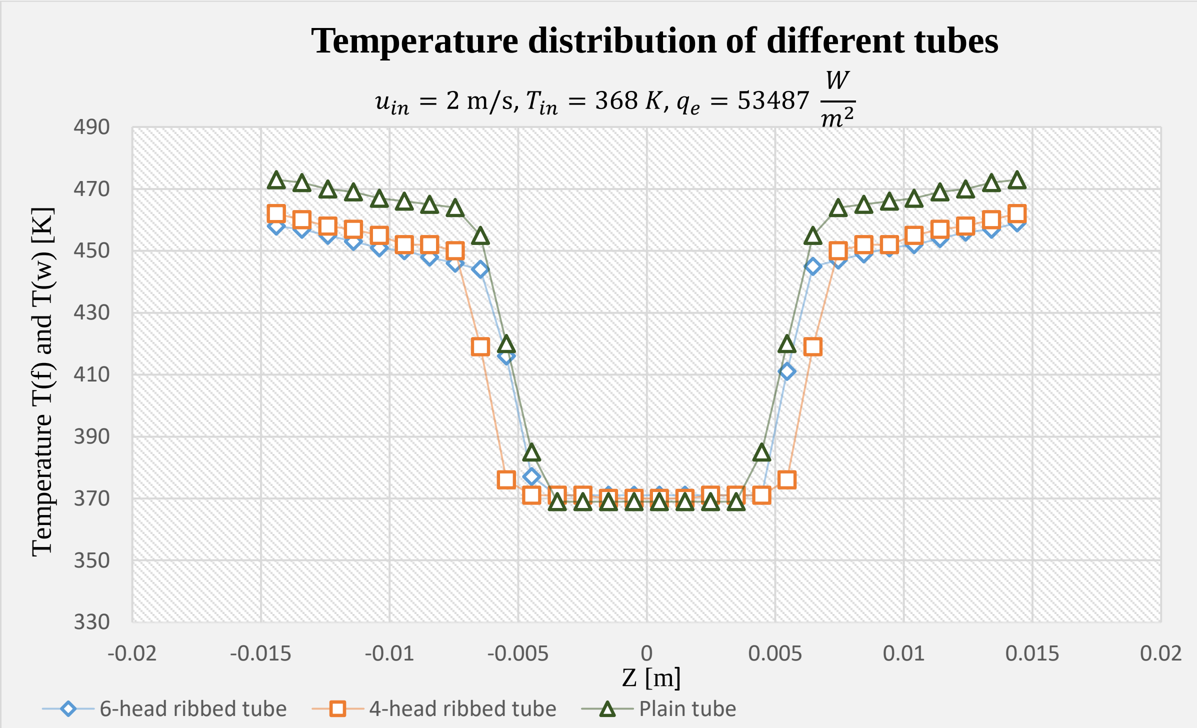

Figure 6.1 Distribution of simulated temperature in different tubes at a given condition.

In this figure radial temperature distribution curve of the three different tube models has been shown at the same boundary condition. The temperature lines being analyzed; comparison can be set among the tube models. Such as, the temperature line of the smooth tube has higher value at the both ends but lowest value at the center zone which indicates the temperature at the tube wall is high but the fluid temperature is the lowest for flow in smooth tube. That means the heat flow from tube wall to the core fluid is lowest in case of flow in smooth tube. Similarly, the temperature line of the four head ribbed tube indicates better heat transfer from the tube wall to the flowing fluid at the core than the smooth tube and finally the heat transfer in the six head ribbed tube is the higher compared to the other two models as the wall temperature has the lowest value and the core temperature has the highest value indicating more heat flow from tube wall to the core fluid. So, in conclusion, it can be said that six head ribbed tube provides the best heat transfer performance among the three tube models.

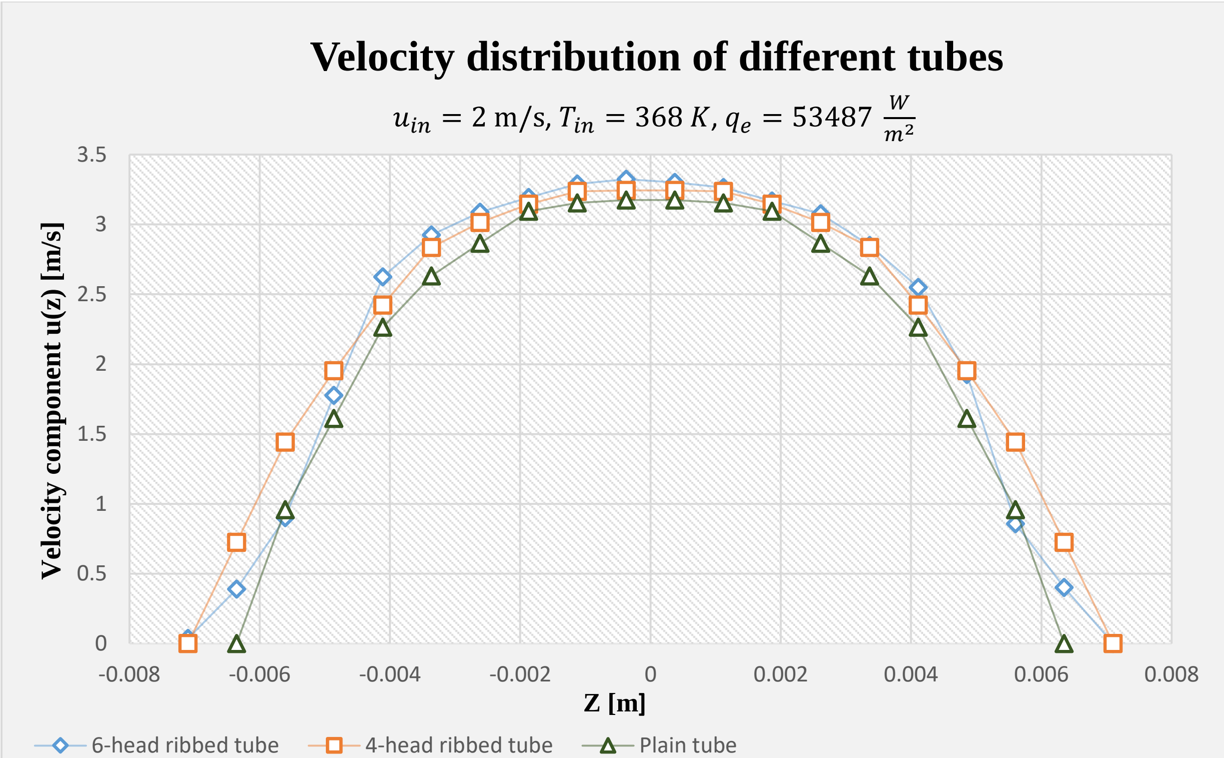

Figure 6.2 Simulated axial velocity of different tubes in a given condition.

In these figure the velocity distribution of the Therminol 55 flowing inside the tube models has been compared. From the graph it is identified that the velocity lines start from zero at its radial points because of no flow condition imposed at the boundary of the flow region. Velocity of fluid in all tubes starts from null value and gradually increases to the center. At the center of the tubes, velocity is lowest for smooth tube as the flow inside this tube is considered to be viscous-linear. Core fluid velocity is higher in four head ribbed tube and highest in six head ribbed tube as shown in the graph. The flow inside the ribbed tubes is considered to be turbulent flow and also the ribs provide swirling effect at the rib vicinity. As a result, centrifugal force is generated which induces rotational flow and increases the relative velocity between the tube wall and core fluid. So, it indicates more turbulence and swirling effect is created in six head ribbed tube which results in higher core velocity of fluid and also higher mass transfer rate at a high temperature through the tube.

Chapter 7

CONCLUSION AND FUTURE SCOPES

The convective heat transfer coefficient and hence Nusselt number of Therminol 55 heat transfer fluid has been investigated by means of numerical simulations in smooth tube, four head ribbed tube and six head ribbed tube. Since the heat transfer rate is highly related to the heat transfer surface, thus the installation of ribs inside the tube results in increasing the heat transfer rate. It is found that the internally ribbed tube can significantly improve the heat transfer. Compared to smooth tube heat transfer rate is increased by 8.2 -13.2% in four head ribbed tube and again compared to four head ribbed tube heat transfer is increased by 1.85-2.88% in six head ribbed tube. Heat transfer is generally related to pressure drop and the pressure drop is significantly increased in four head and six head ribbed tubes.

The investigation is done using Therminol 55 as working fluid and 1Cr18Ni9Ti as the heat exchanger material. It also enables the possibility to further modify and improve the performance of the heat exchanger. One of the possibilities is by changing the heat exchanger material. There are lots of efficient conductive material available and even a significant number of heterogeneous materials are also solving the problems incorporated with efficiency of heat conductors. Another way is by changing the heat transfer fluid. Beside Therminol 55, there are wide variety of Therminol available. The Therminol can be selected based on the application and according to the properties required.

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