Computational Analysis of Heat Transfer Enhancement in Corrugated Pipe using Various Grooves

Nitin Kumar[1], Munendra[2], Pradeep Kumar Gautum[3], Uday Pratap Singh[4], Prof Chandan B B[5]

[1,2,3,4]Student, [5]Assistant Professor
J.S.S. Academy of Technical Education, Noida, U.P., India

***Abstract*: Heat transfer enhancement techniques can be divided into two categories passive and active. In passive heat transfer enhancement an object which does not use external energy, such as groove inside the tube, has the duty of increasing the heat transfer rate. Forced convection heat transfer is the most frequently employed mode of the heat transfer in heat exchangers or in various chemical process plants. Corrugated pipes are used in various engineering applications such heat exchangers and oil transport. In most cases these pipes consist of periodically distributed grooves at the duct inner wall. In the present study there are three shapes of grooves semi-circular, rectangular and trapezoidal with varying depth introduced internally to generally used pipes in heat exchangers to investigate the heat transfer enhancement within the Reynolds number range of 5000 to 12000 with heat flux at the outer walls of pipes. CFD analysis is carried out through Ansys Fluent using K epsilon turbulence model. The Results found to be are that the trapezoidal performs with effectiveness (Nu/Nuo) of 21 to 29% more over rectangular and semi-circular grooved pipe. And also thermal hydraulic performance of 5-8% over circular grooved pipe and 30-50% over rectangular grooved pipe. Trapezoidal grooved pipe also shows least pressure losses over other grooved pipes at all depths.**

***Keywords*: Heat Exchangers, Pressure Drop, Nusselt Number, Thermal Hydraulic Performance**

Introduction

Exchanging heat between fluids at different temperature through a separating solid wall is an important process used in many engineering applications. The shape of the thermal boundary layer is a dominating factor in the efficiency of heat transfer between the fluids. Changing the geometry of the pipes introduces modifications to the thermal boundary layer and opens the potential for a more efficient heat transfer between the fluids.

In the present study the purpose of computational fluid dynamics is to do study on heat transfer, pressure drop, Nusselt number and thermal hydraulic performance of a plain pipe taken as a reference pipe and pipe with grooves at different depths includes semicircular, rectangular and trapezoidal grooves. Working fluid considered here is water and tests were performed for Reynolds number ranges from 5000 to 12000 for plain tube and different geometry inside grooved tubes.

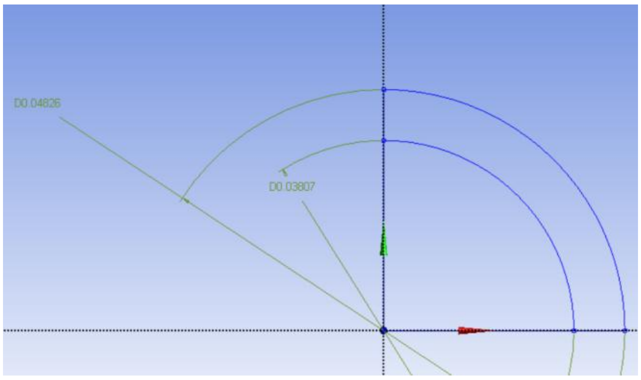
In the previous studies, S. Naga Sarada et. al (2010) conducted experiment and found that the enhancement of heat transfer with twisted tape inserts as compared to plain tube varied from 36 to 48% for full width (26 mm) and 33 to 39% for reduced width (22 mm) inserts. Correlations are developed for friction factors and Nusselt numbers for a full developed turbulent swirl flow, which are applicable to full width as well as reduced width twisted tapes, using a modified twist ratio as pitch to width ratio of the tape. Prof. Shashank S. Choudhari et. al (2015) found that heat transfer characteristics and friction factor of horizontal double pipe heat exchanger with coil wire inserts made up of different materials are investigated. The Reynolds numbers are in the range of 4,000-13,000. The inner and outer diameters of tubes are 17 mm and 21.4 mm respectively. Aluminum, copper, and stainless steel inserts are of pitches 5, 10 and 15 mm respectively. Effect of these coil wire inserts material on enhancement of heat transfer and friction factor are considered. The experimental data obtained from plain tube were verified with the standard correlation to ensure the validation of experimental results. Coil wire has significant effect on heat transfer and friction factor. Cu insert has higher heat transfer enhancement of 1.58 times as compared to plane tube. On other hand Aluminum and stainless steel insert has heat transfer enhancement of 1.41 and 1.31 as compared to plane tube respectively. The friction factor found to be increasing with decreasing coil wire pitch.

Henrique S. de Azevedo et. al (2008) investigated the influence of grooves height and length in the global friction factor of turbulent flow through periodically corrugated pipes. The friction factor increases compared to smooth pipes, and such increase is more significant for higher Reynolds numbers and for larger grooves as well. Ponnusamy Selvaraj et. al (2013) conducted computational fluid dynamics studies on heat transfer, pressure drop, friction factor, Nusselt number. The maximum increase of pressure drop was obtained from numerical modeling 74% for circular, 38% for square, and 78% for trapezoidal grooved tubes were compared with plain tube. Based on computational fluid dynamics analysis the average Nusselt number was increased up to 37%, 26%, and 42% for circular, square and trapezoidal grooved tubes, respectively, while compared with the plain tube. Djamalutdin Chalaev et. al (2016) conducted research of heat transfer and hydrodynamics in the "tube in tube" type heat exchanger with a corrugated inner tube found considerable intensification of heat transfer compared with traditional smooth tube heat exchanger in the range of Reynolds numbers from 4,000 to 40,000. The increasing of heat transfer coefficient was from 2.0 to 2.6 times during the increase of the hydraulic resistance in 1.9 … 2.0 times. It was found that the tubes with the small corrugation height and the big corrugating pitch (height/pitch ratio – 1.9/4.0 mm) have 15 ... 20% higher convective component of the heat transfer coefficient in comparison with tubes with the higher corrugation height and the small corrugation pitch (height/pitch ratio – 2.4/3.2 mm) under identical flow conditions.

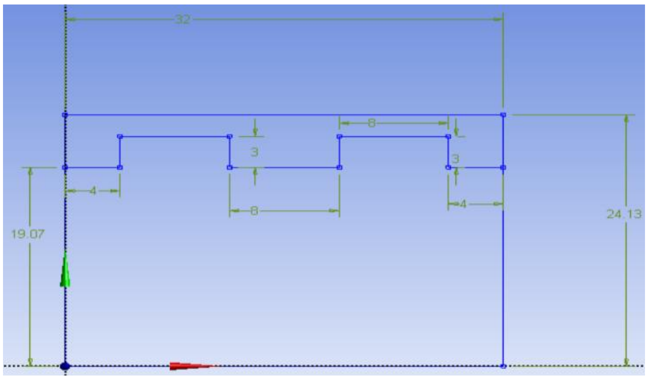
S. Jamshed et. al (2016), A set of three tubes, namely, the simple metallic tube (SMT), the straight groove tube (SGT) and the helically grooved tube with 12-inch pitch (GT12) were numerically studied. Performance criteria through. CFD was based on the heat transfer via Nusselt number as well as the friction factor. For the heat transfer performance, it was evaluated with the thermal performance factor given by (Nu/Nus)/(f/fs), whereas Nu is the Nusselt number and f is the friction factor and subscript 's' is for the smooth tube. Two turbulence models were used, k-epsilon realizable and k-omega Shear Stress Transport. Between the two turbulence models tested and the given range of Reynolds number, it was found that k-ω SST is the most suitable candidate for this range of Reynolds number due to its closeness to the experimental data both in the case of the Nusselt and friction factor. Among the three tubes tested and making the simple metallic tube (SMT) the baseline, the GT12 performed better and has performance factor better than the other two at most of the Reynolds numbers. Mohamed Sakr Fadl (2016), In this study they investigate heat transfer performance and flow development in three different corrugated channel using different rib shapes (Trapezoidal, Triangle and semi-circular), a numerical simulations were carried out for uniform wall heat flux equal 290 W/m^2 for air as a working fluid, Reynolds number varies from 5,000 to 20,000 and three different channel heights (S_{max} = 12.5, 15.0 and 17.5 mm). Governing equations of flow and energy were solved numerically by using FVM (finite volume method). The numerical results indicated that, wavy (corrugated) channels have a significant impact on heat transfer enhancement with increase in the pressure drop thought channel. The effect of corrugation patterns on the heat transfer and fluid flow are more significant in narrow channel especially for trapezoidal and triangle corrugated surface, because they have a sharp edges. Performance evaluation plot was used to analysis the predicted results and compare different heat transfer enhancement techniques towards energy saving which expect give guidelines for selecting the best surface corrugated geometry for designing heat exchanger based on thermal performance and pumping power. The objective of this study is investigate the effect of using different corrugated surface to enhance heat transfer rate in heat exchanger under constant wall heat flux, which leads to produce more compact heat exchanger with higher energy performance, in the same time, evaluate the overall performance [heat transfer and pressure drop] for Reynolds number ranges from 5,000 to 12,000 and different depths [2, 3 and 4 mm]. The present work a CFD modeling was carried out in order to investigate effect of different grooves shape on thermal performance, heat transfer and pressure drop in corrugated channel. The CFD analysis results of this study are expected to provide guidelines for designing heat exchanger to sake the optimal structure design.

Corrugated Geometry

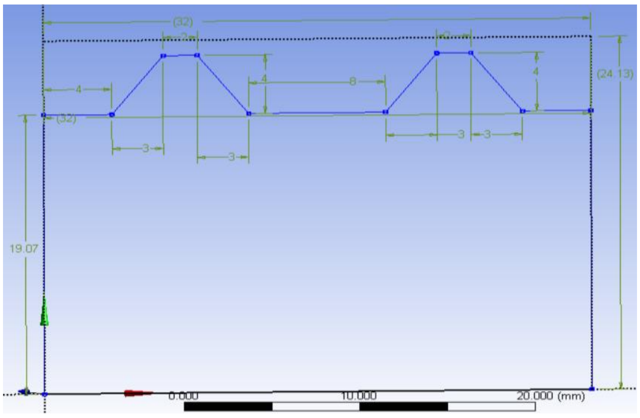
There are three basic geometries of corrugated pipe used in this study which comprises of rectangular, semi-circular and trapezoidal grooves with similar depth. The depth of grooves are varied (2, 3, 4 mm) in all three cases to investigate the thermal performance with each other and simple pipe. Sketch diagram of corrugated pipe and geometrical parameter are shown in Fig 1.



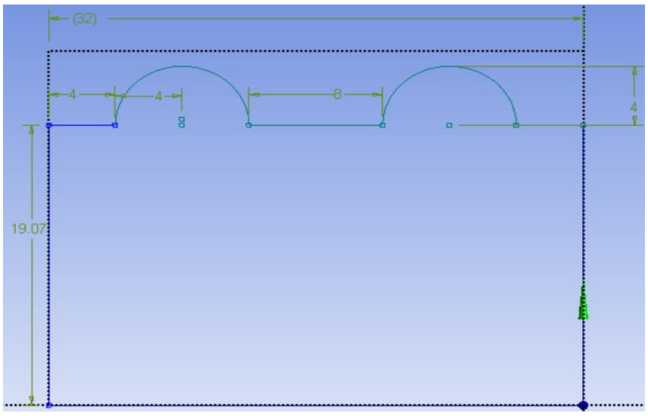
a. Simple Pipe Geometries



b. Rectangular Grooved Pipe Geometry



c. Trapezoidal Grooved Pipe Geometries



d. Semi Circular Grooved Pipe Geometries

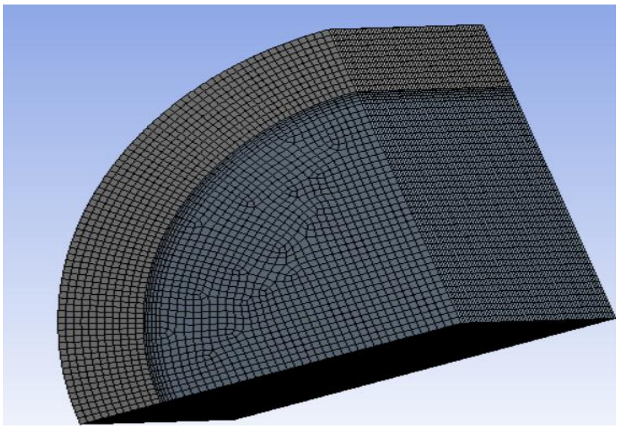
Fig. 1 - Geometries of Simple and Corrugated Pipes

Modelling and Meshing:

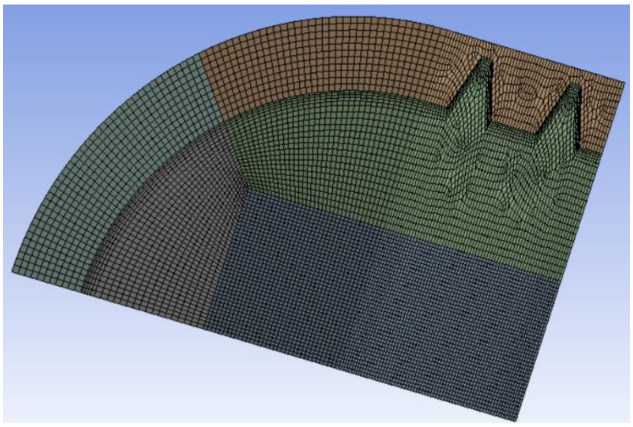
Specifications of the Model:

Length of all pipes considered	= 32mm.
Inner diameter of pipe	= 38.14mm.
Outer diameter of pipe	= 48.26mm.
Groove depths considered	= 2mm, 3mm, 4mm.
Groove length (constant)	= 8mm

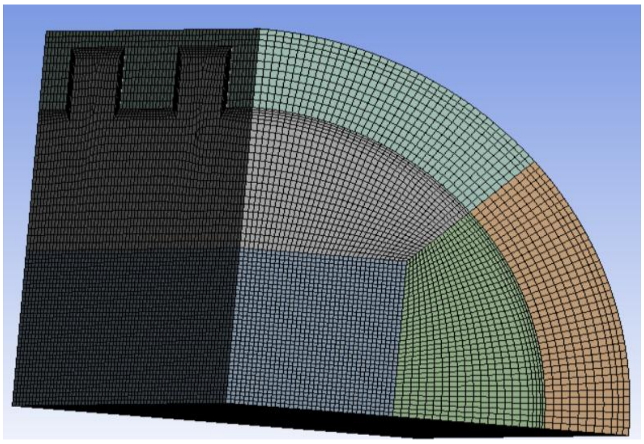
Modelling of pipe is done on Design Modeler and the meshing part is done on ICEM CFD. Modelling and meshing of corrugated pipes are shown in Fig 2.



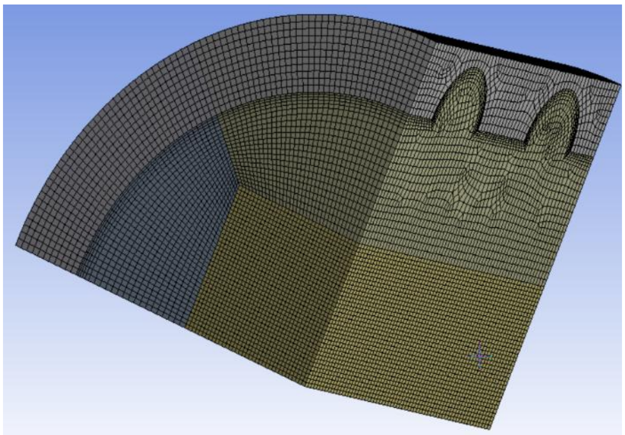
a. Mesh for Plain Profile Model



b. Mesh for Trapezoidal Profile Model



c. Mesh for Rectangle Profile Model



d. Mesh for Circular Profile Model

Fig. 2 - Modelling & Mesh Grid Generated for All Pipes

In this study, Number of elements generated in the grids for all the geometries at all depths are in the ranges of 90,000 to 15,000, the minimum orthogonal qualities are in the range of 0.48 to 0.60 and average values of orthogonal qualities are 0.93 to 0.98, skewness factor of all the grids are in the range of 0.2e-6 to 0.72, y plus value are in the range of minimum 0 to maximum 1.7, so the y plus values are below 2, hence laminar sub layers are easily captured in all the cases.

Governing Equations

The main structure of thermo-fluids examination is directed by governing equations that are based on the conservation law of fluid's physical properties. The basic equations are the three laws of conservation:

- Conservation of Mass: Continuity Equation

$$\frac{\partial \rho}{\partial t} + \nabla = 0$$

- Conservation of Momentum: Newton's Second Law

$$\frac{\partial(\rho\vec{u})}{\partial t} + \nabla(\rho\vec{u}) = \rho g - \nabla P + \nabla$$

- Conservation of Energy: First Law of Thermodynamics or Energy Equation

$$\frac{\partial(\rho e)}{\partial t} + \nabla[\vec{u}(\rho e + P)] = \nabla\left[Keff.\nabla T + \left(\bar{\bar{\tau}}eff.\vec{u}\right)\right]$$

where, $where, \bar{\bar{\tau}} = \mu\left[(\nabla\vec{u} + \nabla\vec{u}^T) - \frac{2}{3\nabla\vec{u}I}\right]$

These principles state that mass, momentum, and energy are stable constants within a closed system. Basically everything must be conserved.

Analytical Calculations

Constant heat flux per unit area for solid wall q/A	=	9699.6W/m^2
Fluid mass flow at the inlet $\dot{m}$	=	0.33kg/s
Inner diameter of the pipe D	=	38.14mm
Density of water ρ	=	1000kg/m^3
Thermal conductivity of water	=	0.6W/m-K
Kinematic viscosity of water	=	1.003x$10^{-6}m^2$/s

We know that

$$R_e = \frac{4\dot{m}}{\rho\pi D\gamma}$$

$$R_e = \frac{4x0.333333333}{1000x\pi x0.03814x1.003x10^{-6}} = 11094$$

The Reynolds number is > 4000, ∴ flow is turbulent

For Fully developed flow using equation 2.3.1, from data hand book, (19)

$$N_u = 0.023R_e^{0.8}P_r^{0.3}$$

P_r = 6.015 for water at 27 °C

∴ $N_u = 0.023 \text{ x } 11094^{0.8} \text{ x } 6.015^{0.4}$

N_u = 81.188

$$N_u = \frac{hD}{k}$$

$$\therefore h = \frac{N_u k}{D} = \frac{81.188x0.6}{0.03814} = 1277.210\text{W/m}^2\text{ K}$$

And we know that q = hAΔT

$$\therefore \frac{q}{A} = h\Delta T$$

$9699.6 = 1277.210\ (T_w - T_b)$
$9699.6 = 1277.210\ (T_w - 300)$

$\therefore T_w = 307.594$ K

Re	$\dot{m}$ in kg/s	Nu	h in W/m2 K	Tw in K
5000	0.15	42.9139	675.092	314.360
6500	0.1952	52.936	832.763	311.647
8000	0.240	62.502	983.251	309.86
9500	0.285	71.71	1128.10	308.59
11094	0.3333	81.188	1277.2	307.594
12000	0.3755	89.32	1405.13	306.90

Table 5.1 Mass Flow Rate, Nusselt Number, Heat Transfer Coefficient and Fluid Wall Temperature at Various Reynolds Numbers

Solution Methodology

The two-dimensional continuity, momentum and energy equations were solved computationally. The standard **k-ε** turbulence model and the Renormalized Group (RNG) **k-ε** turbulent were selected. The upwind and central difference methods were used for convections and diffusions, respectively.

Fully developed turbulent flow was imposed at the inlet for all the grooved channels, flow motion and energy equations are solved numerically by using Fluent tool, different parameters are considered such as Reynolds number, groove depth and groove length, the channel surface considered under constant wall heat flux, the overall performance of the grooved tubes are evaluated in terms of Nusselt number, pressure drop, Effectiveness and Thermal hydraulic performance which are calculated by the aid of numerical results. The solution domain is considered 3D, enclosed by outlet, inlet and wall boundaries. No-slip conditions are assumed for momentum equations on walls so the inlet velocity values have been derived from preferred Reynolds numbers to save the computational time; the periodicity code was used to define hydrodynamics fully developed flow at inlet, the outlet boundary condition is called "pressure outlet", which implies a static (gauge) pressure at the outlet boundary, which means the pressure will be extrapolated from the flow in the interior.

Results and Discussions

The numerical results obtained for the three different grooves proposed for depths of 2 mm, 3 mm, 4mm and the plain pipe as well as relevant physical interpretations related to the observed turbulent flow pattern. The fluid properties assumed are density $\rho = 1{,}000$ kg/m^3 and kinematic viscosity $\nu = 1.003 \times 10^{-6}$ m^2/s, and the Reynolds numbers 5,000, 6,500, 8,000, 9,500 and 11,094 are simulated. The following results are on the based on performance parameters:

Pressure Drop

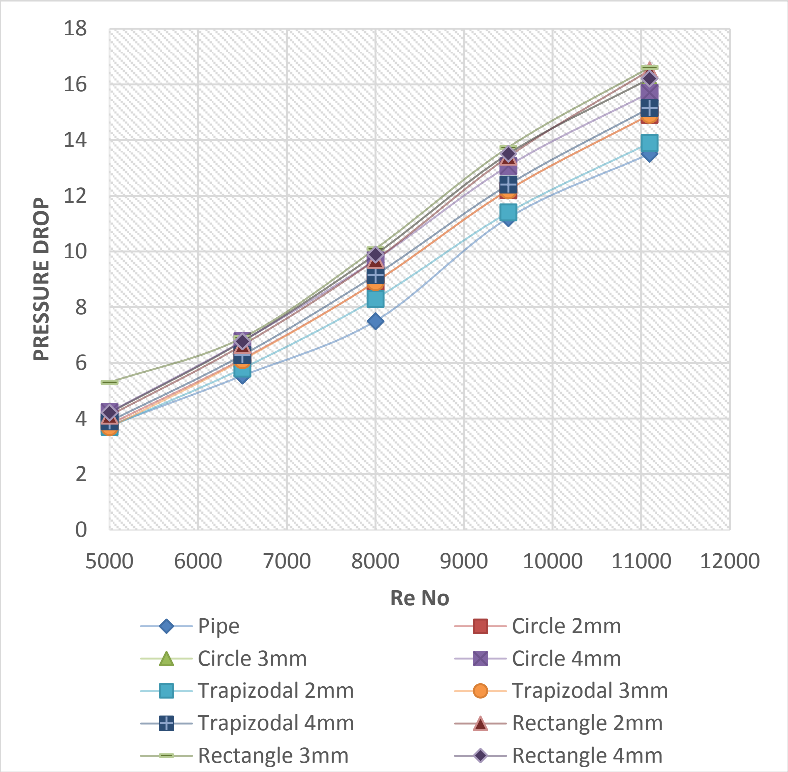


Fig. 4 - Variation of Reynolds Number with Pressure Drop for All Pipes

Pressure drop is also one of the main parameter in fluid dynamics to analyze the flow effects. Variation of pressure drop for various Reynolds numbers and various grooves is represented in the Fig. 4, Usually pressure drop increases by increasing the length of pipe or area of flow through pipes, if the pressure drop increases, requirement of energy is increased to pump the fluid into the system, and from the graphs we can clearly observe that rectangular groove has high pressure drop compared to all other groove shapes at all depths because of its sharp edges and also due to the formation of vortex in rectangle grooves , so always it is better to choose the groove in balancing way such that, the groove with higher heat transfer co-efficient at acceptable pressure drop depending on the requirements.

Nusselt Number and Heat Transfer Coefficient

Nusselt number is the very important parameter to study the thermal effects on fluid flow especially for forced convection, the above Fig. 5 clearly indicates that as Reynolds number increases Nusselt number also increases. Generally, the increase in Nusselt number indicates an enhancement in heat transfer co-efficient due to increase of convection heat transfer. The overall results show that when the tube is equipped with internal grooves, the Nusselt numbers is higher than those obtained for the plain tube and as the depth increases the circulation of fluid also increases. It has been observed that the value of Nusselt number has been seen highest in case of trapezoidal groove with 4mm depth and lowest in the rectangular groove 2 mm. As the depth increases the convection increases because of better circulation of fluid. As the Nusselt number is directly proportional to heat transfer coefficient it shows same way graph as Fig. 5.

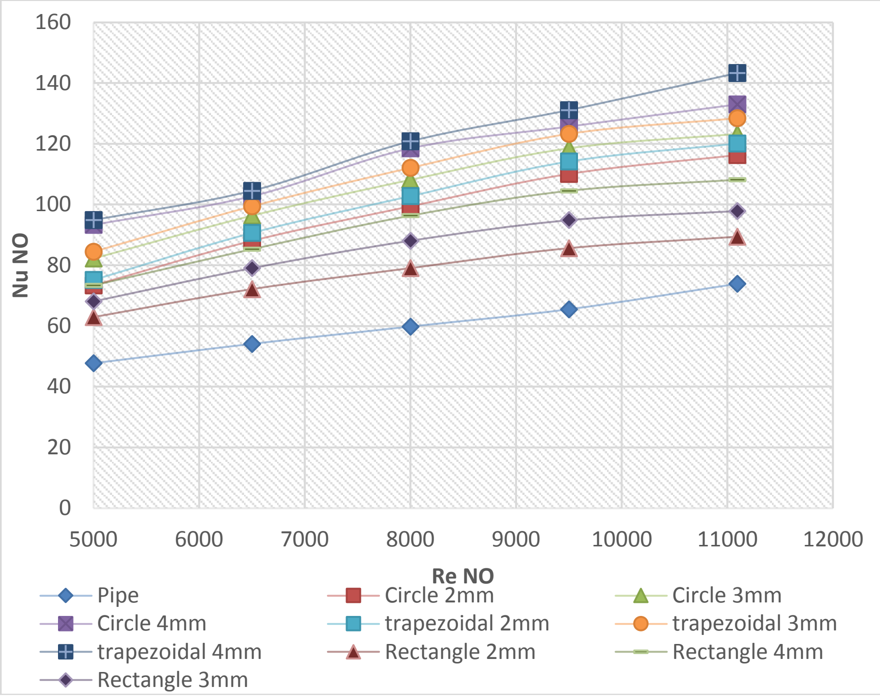


Fig. 5 - Variation of Reynolds Number with Nusselt Number for All Pipes

Effectiveness (Nu/Nuo)

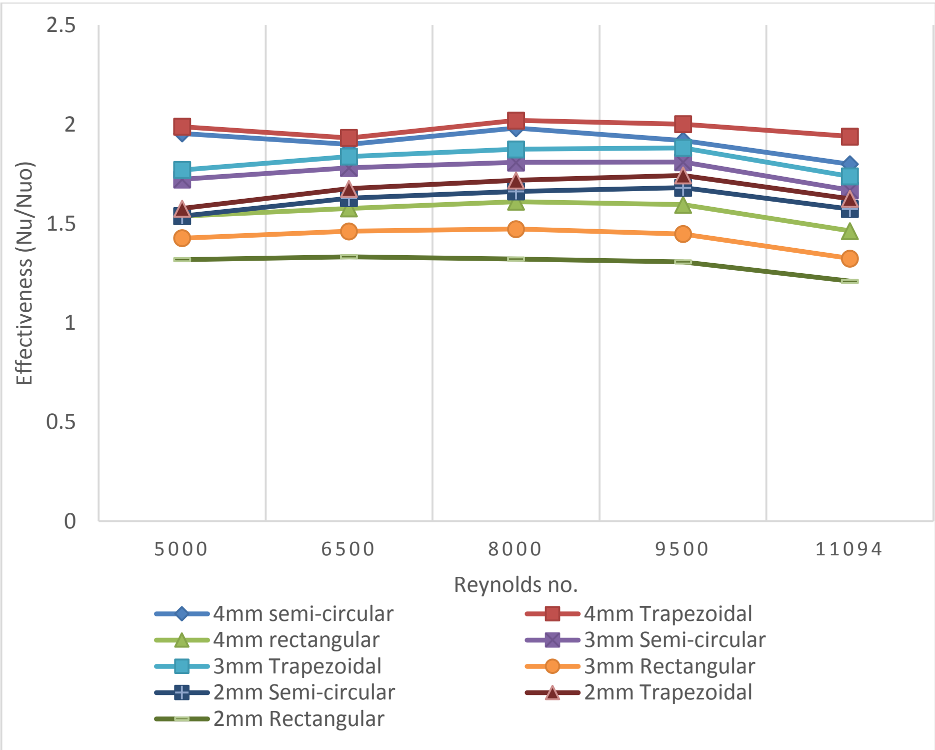


Fig. 6 Variation of Reynolds Number with Effectiveness for All Grooves at All Depths

In fluid dynamics, Effectiveness is the ratio of Nusselt number of grooved pipe to the Nusselt number of plain or reference pipe, from the above plots from Fig. 6 we can clearly observe that trapezoidal grooved pipe is more effective for all ranges of Reynolds numbers and at all depths, so it clearly indicates that Nusselt number is dominating more in case of trapezoidal grooved pipe than all other groove shapes, after the trapezoidal groove pipe, semi circular groove pipe always try to settle at the middle in almost cases, effectiveness parameter will be very effective parameter, if one's concentration is majorly on heat transfer co-efficient irrespective of the pressure loss.

Thermal Hydraulic Performance [(Nu/Nuo)/(f/fo)]

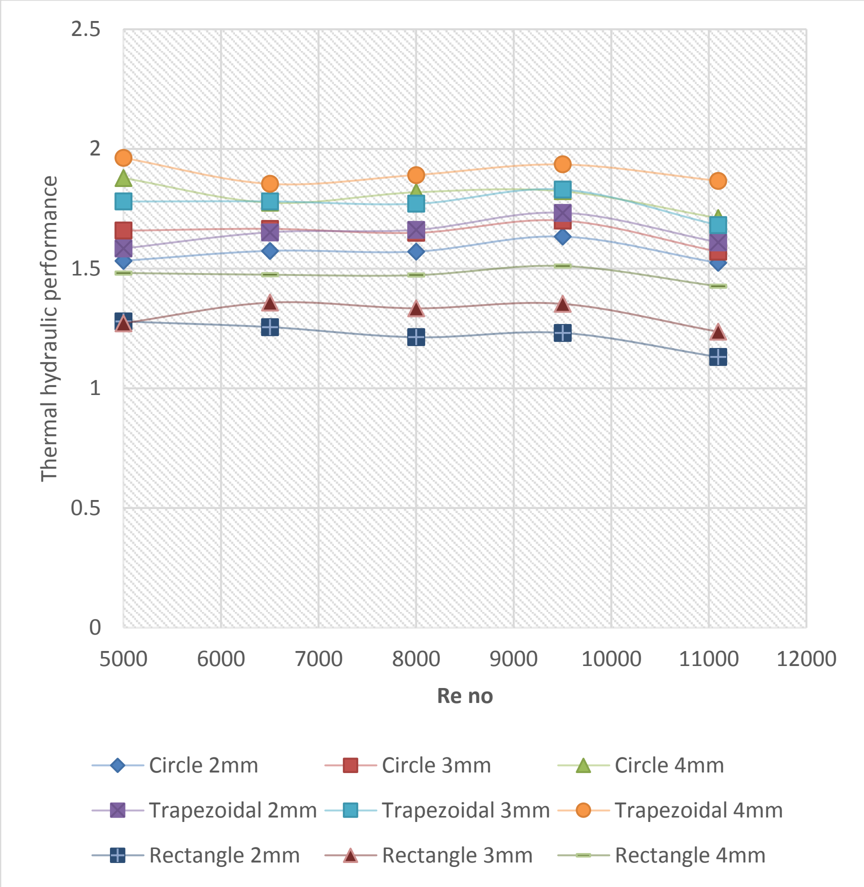


Fig. 7 - Variation of Reynolds Number with Thermal Hydraulic Performance for All Grooves and All Depths

Thermal hydraulic performance or Heat transfer performance is the one parameter which gives a proper idea on selecting the grooved pipe when we need a pipe which gives a balanced effect of both heat transfer co-efficient and friction factor, the Fig 7 shows a heat transfer performance of all grooved tubes at all depths for various Reynolds numbers, the Fig 7 clearly shows trapezoidal grooved pipe has a higher heat transfer performance at all depths and for almost all ranges of Reynolds numbers compared to all other groove shapes, in the previous studies rectangular grooved pipe has higher effectiveness in all the cases, but rectangular grooved pipe is lagging when it comes to thermal hydraulic performance, Trapezoidal grooved pipe is not lagging in effectiveness, it maintains its consistency in all flow parameters taken in this study and its dominating in the main parameter Thermal Hydraulic Performance.

Conclusion

- In this study different grooved tube like semicircular, rectangular and trapezoidal were introduced into this analysis. Numerical simulation results and graphs shows that in terms of heat transfer enhancement all the grooves are working better than the plain pipe.
- Different depths with different groove shapes also show that reduction in total pressure loss as the depth increases as in case of trapezoidal grooved pipe 4mm depth and in rectangular grooved pipe there is high pressure loss at all depth in comparison to all other grooved pipe.
- Compared to smooth pipe, the mean heat transfer coefficient in corrugated pipe increased by 18 to 75% depending on the shape & depth of corrugation.
- The best shape and depth which shows adequate heat transfer enhancement that found to be in trapezoidal grooved pipe with 4mm depth. It gives improvement of 97% in Nusselt no and 75% in heat transfer coefficient over simple pipe.
- Trapezoidal corrugation provides less Pressure drop and better circulation or mixing of fluid in comparison to other pipes with effectiveness (Nu/Nuo) of 21 to 29% more over circular and rectangular grooved pipe.
- The thermal hydraulic performance has been seen high in trapezoidal grooved pipe with improvement of 5-8% over circular grooved pipe and 30-50% over rectangular grooved pipe.

Scope for Future Work

- In this study, Analysis was carried out by considering only internal grooves with various shapes; study can also be carry out by making external grooves with same geometric profiles considered.
- Further study can be carried out by introducing different shapes of grooves with different dimensions.
- Same could be conducted with higher Reynolds number ranges.

- Further study with same profile & introducing other heat transfer technique like inserts to study the enhancement of heat transfer.

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