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Numerical Analysis of Solar Heat Exchanger with Different Types of Ribs to Enhance Heat Transfer

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Abstract: The solar heat exchanger is used for transferring solar energy to another medium. To increase the heat transfer rate many researchers optimized the different process parameters of the solar heat exchanger. Here in this work, it performs the numerical analysis of solar heat exchanger. To calculated the effect of different Reynolds number on heat transfer here it considered four different Reynolds number that is 500, 900, 1300 and 1700. Here in this work, considered solar heat exchanger with different shapes of ribs inside the heat exchanger, for calculating the effect of the shape of ribs, it considered three different types of rib that are circular, square and triangular shape rib and calculate the value of heat transfer coefficient at different Reynolds number. After analyzing rib type solar heat exchanger for simple water flow, it is then considered for nanofluid flow. For calculating the effect of ribs on nanofluid flow here it considered Titanium-oxide nanofluid for all different types of ribs and calculate the value of heat transfer coefficient.
Keywords: Solar heat exchanger, nanofluid, ribs, single phase model, multiphase model

I. INTRODUCTION

Nanotechnology is a branch of science and technology which makes use of the particles in the nanoscale order, namely in the molecular and atomic order respectively. In this field, the particles considered are analyzed individually from their bulk specifications. The properties of the bulk materials, on the whole, are expected to remain unchanged, whereas at the nanoscale order these properties alter. When these solid particles of nanoscale order are dispersed in any fluid medium known as the base fluids collectively they are stated as nanofluids. In this study, the behavior of these nanofluids is analyzed when they are used in the solar heat exchangers. Many researchers discuss the synthesis of nanofluids, but first, it is necessary to understand what heat exchangers are and what its various types. A heat exchanger is a device that exchanges the heat between two or more flowing fluids. In simple words, one flowing fluid is at the lower temperature, called the cold fluid, and the other fluid is at the higher temperature, called the hot fluid, from which heat has to be extracted.

A. Nanoparticles

Nano derived from Greek word "Nanos" which mean dwarf or very small. The Nanoparticle, ultrafine unite with dimension measured in nanometers. Nanoparticles exist in the natural world and are also created as a result of human activities. Because of their Nano size, they have unique material properties, and manufacture nanoparticles may find practical application in the variety of areas, including engineering, medical and environmental remediation.

Heat transfer from solar heat exchanger depends on the different parameters of the heat exchanger and working fluid. Many researchers use nanofluid to increase heat transfer rate, because of nanofluid the heat carrying capacity of working fluid increases which enhance the heat transfer rate. Some of the researchers optimize the flow velocity to increase heat transfer rate form heat exchanger. Here in this work, Author has analysed both that is simple water flow solar heat exchanger and Titanium oxide-water nanofluid flow heat exchanger.

To increases the heat transfer rate, here it considered three different types of solar heat exchanger geometry that is having circular, square and triangular ribs. For analyzing nanofluid flow numerically, here it considered two different phase model that is single phase flow model and multiphase flow model.

To calculate the effect of a change in Reynold number of working fluid on heat transfer here it considered four different Reynolds numbers that are 500, 900, 1300, and 1700. On the basis of different process parameters and geometry here in the work, it calculated the value of average heat transfer coefficient ratio (h_{avg}) which is the ratio of heat transfer coefficient of nanofluid to heat transfer coefficient of simple water.

B. Mathematical Model Used

Here in this section, it contains the mathematical relations that are used to calculate the value of the nanofluid property at a particular volume concentration of nanoparticles. Here in this work, it considered Titanium oxide (TiO_2) as a nanoparticle to make nanofluid at a volume fraction of one percentage. For the single phase fluid flow of nanofluid in numerical analysis, first, it calculates the properties of water and nanoparticle combined to calculate the property of nanofluid. For calculating the property of nanofluid following mathematical calculations were used.

For calculating the density of nanofluid

$$\rho_{nf} = v\rho_s + (1 - v)\,\rho_w$$

Where ρ_{nf} the density of nano fluid is, v is the volume fraction of nano fluid, ρ_s is the density of base material of nano particles, ρ_w is the density of water.

For calculating the Viscosity of nanofluid

$$\mu_{nf} = \mu_w(1 + 2.5v)$$

Where μ_{nf} is the dynamic viscosity of nano fluid, μ_w dynamic viscosity of water and v is the volume fraction of nano particles.

For calculating the specific heat

$$C_{pnf} = \left[v(\rho_s C_{ps}) + (1 - v)(\rho_w C_{pw})\right]/\rho_{nf}$$

Where C_{pnf} is the specific heat of nanofluid, C_{ps} specific heat of nanoparticles base material, C_{pw} specific heat of water.

For Calculating Thermal conductivity

$$K_{nf} = K_{bf}\frac{\left[K_p + 2K_{bf} + 2(K_p - K_{bf})V\right]}{\left[\left[K_p + 2K_{bf} - (K_p - K_{bf})V\right]\right]}$$

K_{nf} is the thermal conductivity of nano fluid, K_{bf} is the thermal conductivity of base fluid, K_p is the thermal conductivity of nano fluid, V is the volume fraction of nano particle.

1) Continuity equation

$$\nabla\,(\rho_e v) = 0$$

2) Momentum equation

$$\nabla\,(\rho_e v v) = -\nabla p + \nabla(\mu_e \nabla v)$$

3) Energy equation

$$\nabla\,\left(v(\rho C_p)T\right) = \nabla(k\nabla T)$$

II. DEVELOPMENT CFD MODEL OF HEAT EXCHANGER

In order to perform the numerical analysis of solar heat exchanger here first, Author has to develop the CFD model of the solar heat exchanger. In order to perform the CFD analysis first, Author has developed the solid model of the solar heat exchanger on the basis of geometry considered during the experimental analysis performed by Bajestan et.al [1].

A. Development of a Solid model of the Solar Heat Exchanger

Solid model of solar heat exchanger depends on the geometric condition as considered in base paper the geometric parameters were shown in the below table.1

Table.1 Shows the value of a geometric parameter of the solar heat exchanger

Parameter	Value
Tube inner diameter	7.8 mm
Tube outer diameter	9.6 mm
Tube length	2000 mm

On the basis of above mention geometric parameters of solar heat exchanger here bases on research developed the solid model of heat exchanger. The solid model of heat exchanger is shown in the below fig. 1

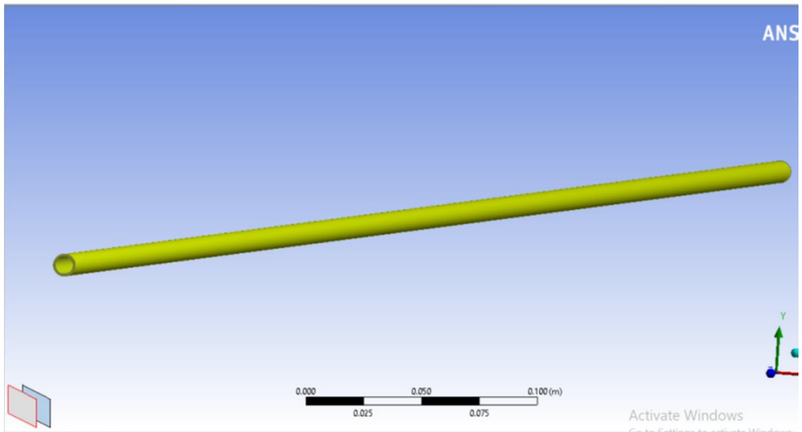

Fig.1 Solid Model of Solar Heat Exchanger

B. Meshing

Numerical analysis work on a number of nodes and elements, so to perform the numerical analysis of solar heat exchanger first, discretize the solar heat exchanger into a number of elements and nodes. To calculate the independence of a number of node and elements here it performs meshing of the solar heat exchanger with different numbers of nodes and elements. To perform the independence test here it discretized the complete body of the solar heat exchanger with four different number of the element.

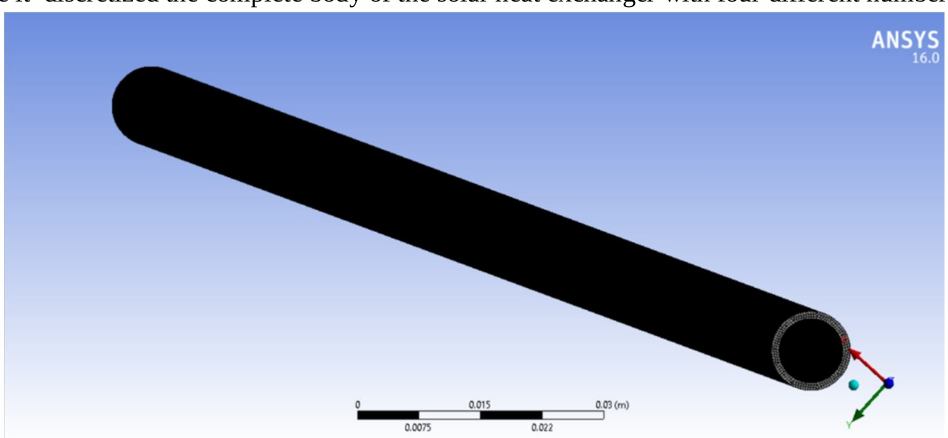

Fig.2 Mesh of the tube heat exchanger

C. Model Selection

Here in this work, it first considered water as a working fluid for that it considered single phase model with steady state condition. After analyzing water at different Reynolds number for different geometry, it considered titanium-oxide nanofluid for that it considered the multiphase model.

D. Material Selection

Here in this analysis water is considered as the working fluid, which is flowing inside the pipe with different mass flow rate. Copper material is considered for the manufacturing of pipe. Whereas titanium oxide at 1% is considered for the preparation of nanofluid, the properties of the different materials are shown below.

1) *Water :* Water is considered as a working fluid for the initial case of study to validate the CFD model of the solar heat exchanger as considered for the experimental analysis performed in the base paper. The properties of water used by CFD modelling is mention in table 2.

Table.2 Properties of water

Properties	Value
Density (ρ) kg/m^3	998
Specific heat (C_p) J/kg-K	4182
Thermal conductivity (K) W/m-k	0.6
Viscosity (μ) Pa-s	0.00089

2) *Titanium oxide (TiO$_2$):* After use of water in the solar heat exchanger, titanium oxide nanoparticles were added in water to increase the heat transfer rate of solar heat exchanger. Here in this analysis titanium oxide is added into the water at 1% of volume fraction, titanium nanoparticles are of 40e-09 size in diameter. The properties of titanium oxide nanoparticles were mention in the below table 3

Table.3 Properties of nano particles

Properties	Value
Density (ρ) kg/m^3	4157
Specific heat (C_p) J/kg-K	710
Thermal conductivity (K) W/m-k	8.4

3) Copper: Here in this work, the tube of the solar heat exchanger in which water is flowing is made of copper. The properties of copper are mention in the below table 4

Table.4 Properties of Copper

Properties	Value
Density (ρ) kg/m^3	8978
Specific heat (C_p) J/kg-K	381
Thermal conductivity (K) W/m-k	387.6

E. Boundary Condition

To perform numerical analysis of solar heat exchanger here, apply different boundary condition at different components of heat exchanger. Here in this analysis, it has considered four different Reynolds number of inlet fluid, for calculating the value of inlet velocity form different Reynolds number following calculation where used

$$Re = \frac{\rho V D}{\mu}$$

Where Re is the Reynolds number, V is the velocity, D is the diameter of the tube, ρ is the density of the fluid flowing inside the tube, μ is the dynamic viscosity. The values of velocity for different Reynolds number is shown in table 5. Here in this analysis the temperature of fluid at the inlet of solar heat exchanger is 298 K. whereas heat flux is applied at the inner wall of pipe for providing the heat flux, a 313 W coil is wounded on the pipe and on the basis of 313 W power here calculated the value of heat flux through following formula

$$\text{Heat flux} = \text{Power / Surface area of the pipe}$$
$$= 313/(\pi DL)$$

Where D is the outer diameter of pipe and L is the length of pipe

Therefore,

Heat flux = 6387.755 W/m^2

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Table.5 Value of velocity for different Reynolds number

Re Number	Velocity
500	0.057
900	0.102
1300	0.148
1700	0.194

F. Validation of the CFD model

To validate the CFD model of solar heat exchanger first it analyzed the water as a working fluid as considered during experimental analysis performed in the base paper. For validating the model it considered same boundary condition as considered during experimental analysis and calculate the value of heat transfer coefficient. After calculating the value of heat transfer coefficient numerically, it is then compared with the value of heat transfer coefficient obtained from the experimental analysis performed in the base paper. For validation, water is considered as a working fluid.

Table.6 Shows the value of heat transfer coefficient for different Reynolds number

S.No	Reynolds No.	Heat transfer coefficient (h) W/m^2K through Numerical analysis	Heat transfer coefficient (h) W/m^2K through Experimental analysis	Error %
1	500	362	405	10.61
2	900	412	460	10.43
3	1300	473	510	7.45
4	1700	502	540	7

After performing the numerical analysis of solar heat exchanger it is found that the value of heat transfer coefficient for different Reynolds number is close to the value of heat transfer coefficient obtained from the experimental analysis performed in the base paper. After analyzing the above mention graph it is found that the numerical analysis of solar heat exchanger is correct.

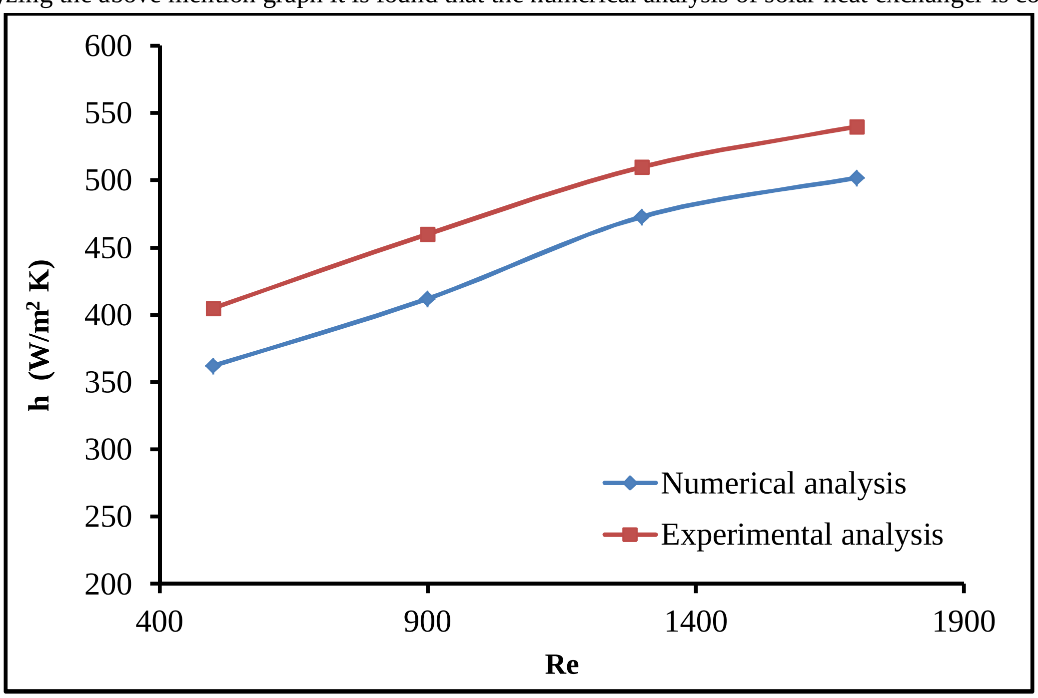

Fig.3 Comparison of value of heat transfer coefficient for different Reynolds number

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IV. RESULT

After validating the CFD model of the solar heat exchanger, it has considered three different geometry of solar heat exchanger that is solar heat exchanger having different shapes of ribs inside the pipe of the solar heat exchanger to increase the heat transfer rate. Here in this work, it analyzed the effect of different shapes of ribs inside the heat exchanger at different Reynolds number for water and nanofluid both. For analyzing the effect of shapes of ribs on heat transfer considered circular, square and triangular shapes of ribs having same cross-sectional area. It has also analyzed the effect of ribs on heat transfer during nanofluid flow, and also analyzed the effect of single-phase and multi-phase flow on heat transfer.

A. For Water As a Working Fluid

Here, in this case, water is used as a working fluid inside the solar heat exchange and calculated the value of heat transfer coefficient for the different geometry of solar heat exchanger as different Reynolds number.

1) *For Circular Ribs:* Here, in this case, a circular shape rib is used to increase the heat transfer from solar heat exchanger, here it considered 2 mm diameter cylindrical with 1 mm height is placed inside the pipe to increase heat transfer. The solid model of a solar heat exchanger having circular ribs inside the heat exchanger is shown in fig.4, during the analysis, consider nine circular ribs inside the pipe having the same diameter with pitch distance 0.2 m.

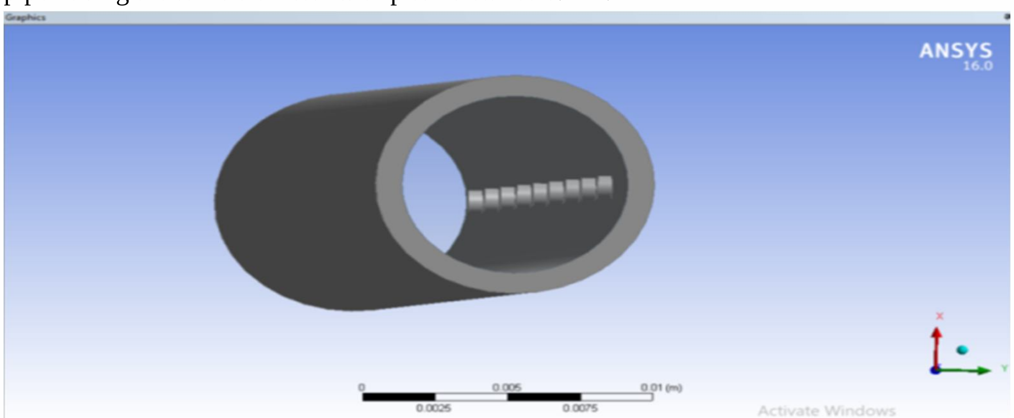

Fig.4 solid model of solar heat exchanger having circular ribs

Table.7 Value of Heat transfer coefficient for a solar heat exchanger having circular ribs

S. No.	Reynolds Number	Heat transfer coefficient (W/m^{2}K)
1	500	501
2	900	557
3	1300	617
4	1700	662

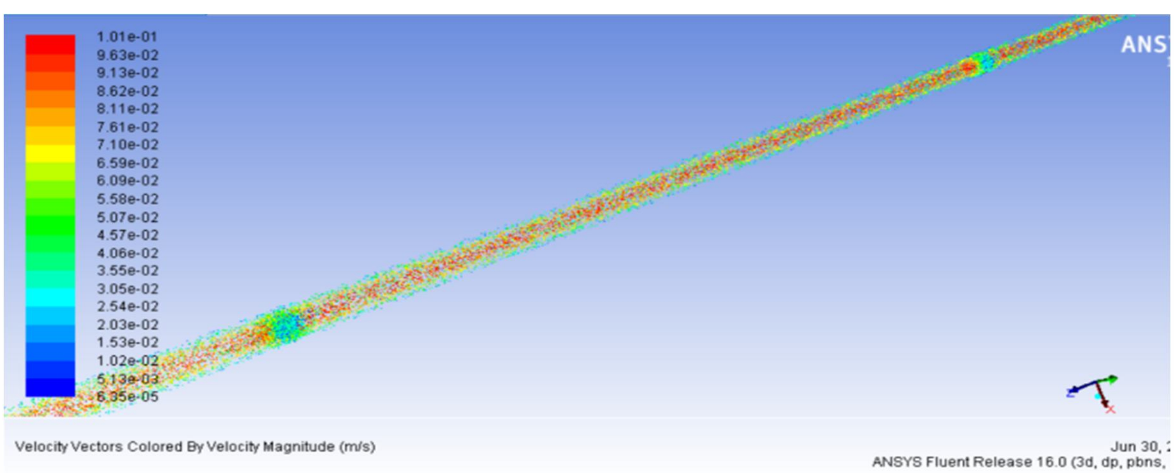

Fig.5 velocity vectors throughout the heat exchanger having circular ribs

2) *For Square Ribs:* Here, in this case, a square shape rib is used to increase the heat transfer from solar heat exchanger, here it considered 1.77 mm side square with 1 mm height is placed inside the pipe to increase heat transfer.

Table.8 Value of Heat transfer coefficient for a solar heat exchanger having square ribs

S. No.	Reynolds Number	Heat transfer coefficient (W/m^2K)
1	500	610
2	900	663
3	1300	709
4	1700	744

3) *For triangular ribs :* Here, in this case, a triangular shape rib is used to increase the heat transfer from solar heat exchanger, it considered 2.69 mm side equilateral triangle with 1 mm height is placed inside the pipe to increase heat transfer.

Table.9 Value of Heat transfer coefficient for a solar heat exchanger having triangular ribs

S. No.	Reynolds Number	Heat transfer coefficient (W/m^2K)
1	500	478
2	900	535
3	1300	582
4	1700	637

B. Comparison Of Different Types Of Ribs Used In Solar Heat Exchanger With Water As A Working Fluid

The graph as shown in fig.6 compares the value of heat transfer coefficient for different types of ribs used in solar heat exchanger at different Reynolds number.

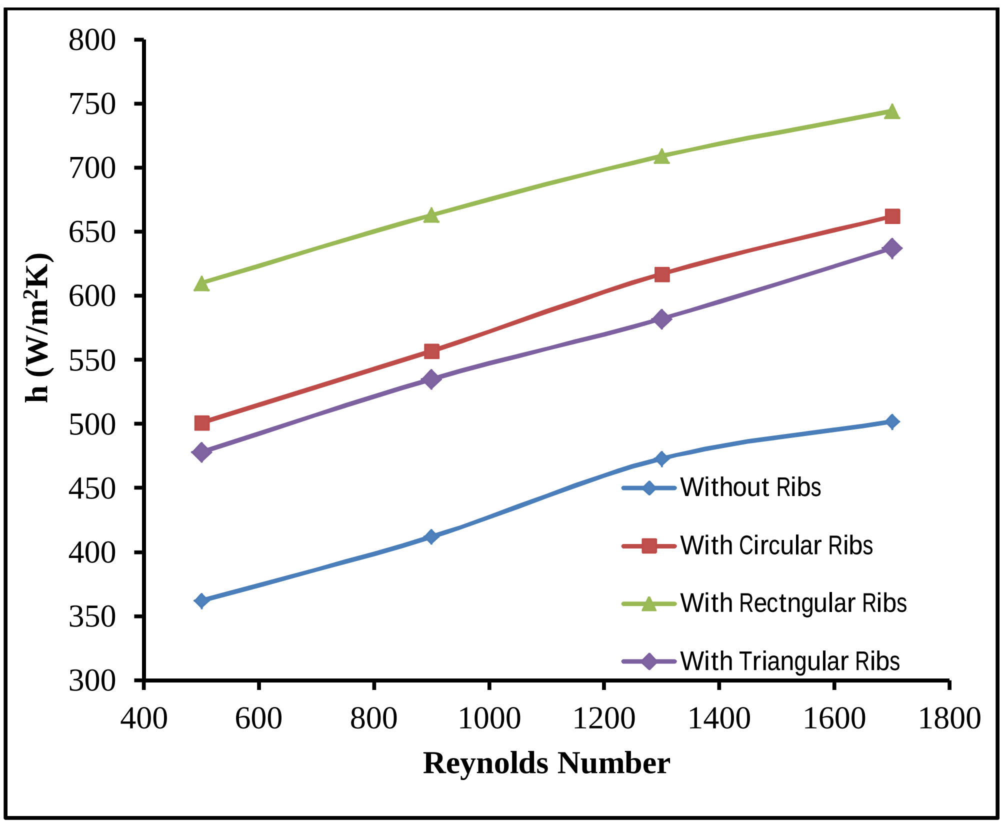

Fig.6 shows the comparison of different types of ribs used inside the heat exchanger

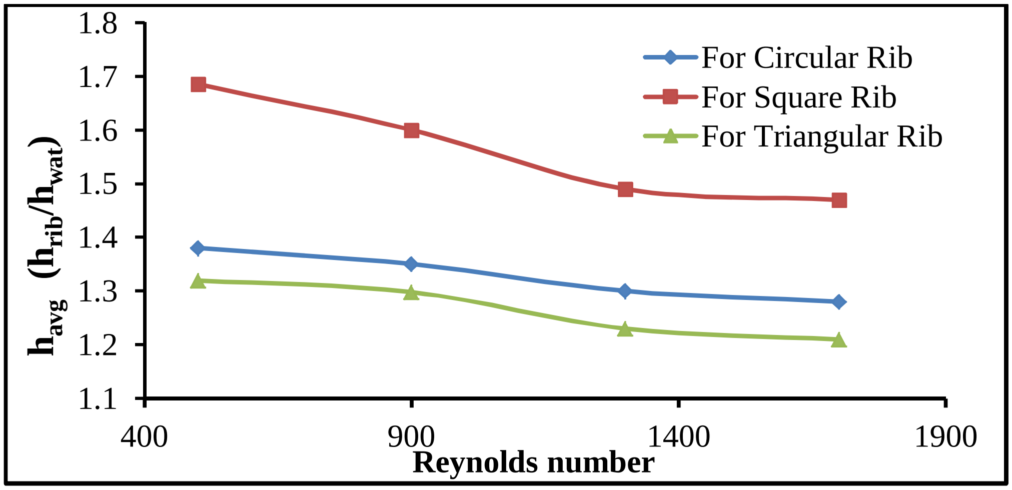

Fig.7 Value of the average heat transfer coefficient ratio for a different rib with simple water flow as a working fluid

From the above comparison graph, as shown in fig.7, it is found that the value of heat transfer coefficient for different Reynolds number is higher for a solar heat exchanger having square types ribs as compared to the other types of ribs used in solar heat exchanger. Through graph, it is also analyzed that the value of heat transfer coefficient for all types of ribs used in heat exchanger is more as compared to the solar heat exchanger without ribs.

C. For Nanofluid

To analyze the effect of ribs on heat exchanger, where nanofluid is used as a working fluid here it considered titanium-oxide-water nanofluid with 1% volume fraction of titanium oxide. In order to solve nanofluid numerically, it considers both single-phase model and multiphase model.

1) For Titanium Oxide as a Nanofluid at 1%

Table.10 Comparison of heat transfer coefficient of nanofluid

S.No	Reynolds No.	Heat transfer coefficient (h) W/m^2-k through Numerical analysis	Heat transfer coefficient (h) W/m^2-k through Experimental analysis	Error %
1	500	460	475	3.15
2	900	487	505	3.56
3	1300	518	535	3.17
4	1700	542	555	2.34

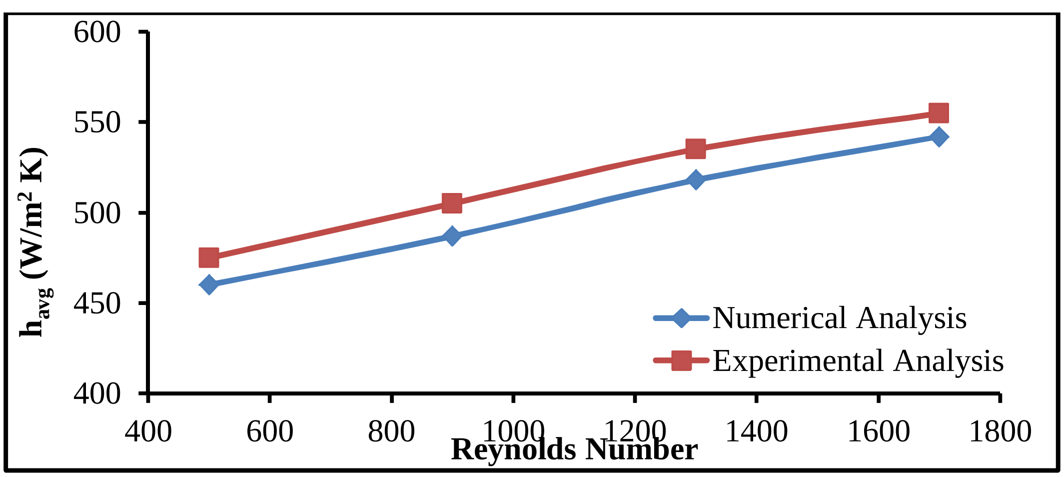

Fig.8 Comparison of the value of heat transfer coefficient of nanofluid

After validating the multiphase model for nanofluid solar heat exchanger without ribs, it analyses the flow of nanofluid in a solar heat exchanger having different types of ribs. For analyzing the effect of different types of ribs used during nanofluid flow in solar heat exchanger it considered three different shapes of ribs that is circular, square and triangular as considered during the numerical analysis of solar heat exchanger

2) *Comparison of Different Ribs for Nanofluid flow:* Here compares the value of heat transfer coefficient for different types of ribs used in solar heat exchanger in which titanium-oxide-water nanofluid is flowing. The comparison of heat transfer coefficient is shown in the below fig.9

Table.11 value of heat transfer coefficient for different ribs

Reynolds number	Heat transfer coefficient (W/m^2-k) for circular rib	Heat transfer coefficient (W/m^2-k) for square rib	Heat transfer coefficient (W/m^2-k) for triangular rib
500	625	682	608
900	658	716	643
1300	689	754	674
1700	724	787	708

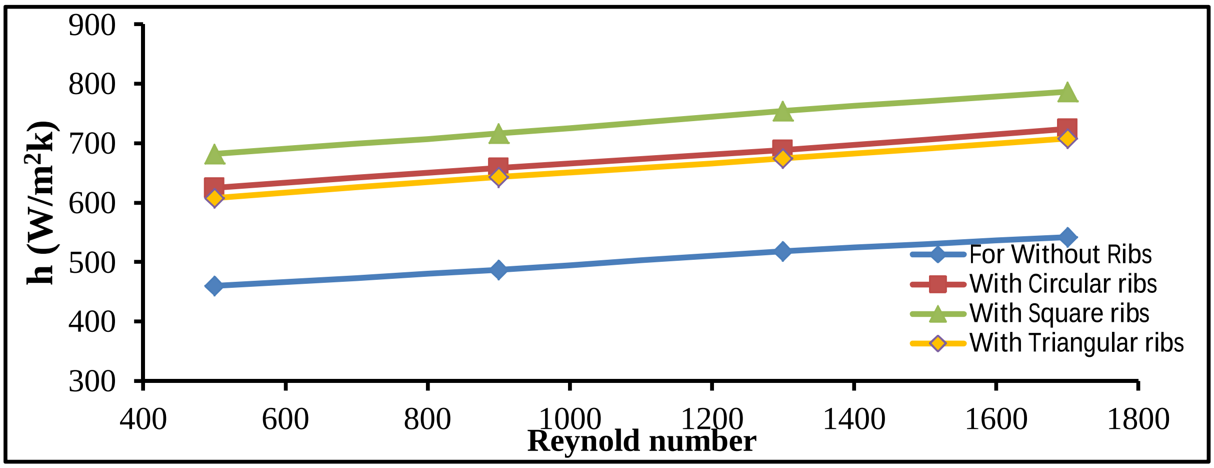

Fig.9 comparison of different types of ribs for nanofluid

Value of average heat transfer coefficient ratio for a heat exchanger having different types of ribs with nanofluid as a working fluid is shown in the below fig.10

From the above graph, it is found that the value of heat transfer coefficient for different Reynolds number is higher in case of a solar heat exchanger having square ribs. Whereas the heat transfer coefficient for all solar heat exchanger having ribs is more as compared to without ribs nanofluid flow heat exchanger. Through analysis, it is also analyzed that the nanofluid increases the heat transfer rate and using ribs in nanofluid flow enhance more heat transfer. After analyzing both that is simple water flow and nanofluid flow it is concluded that solar heat exchanger having square ribs shows higher heat transfer as compared to other.

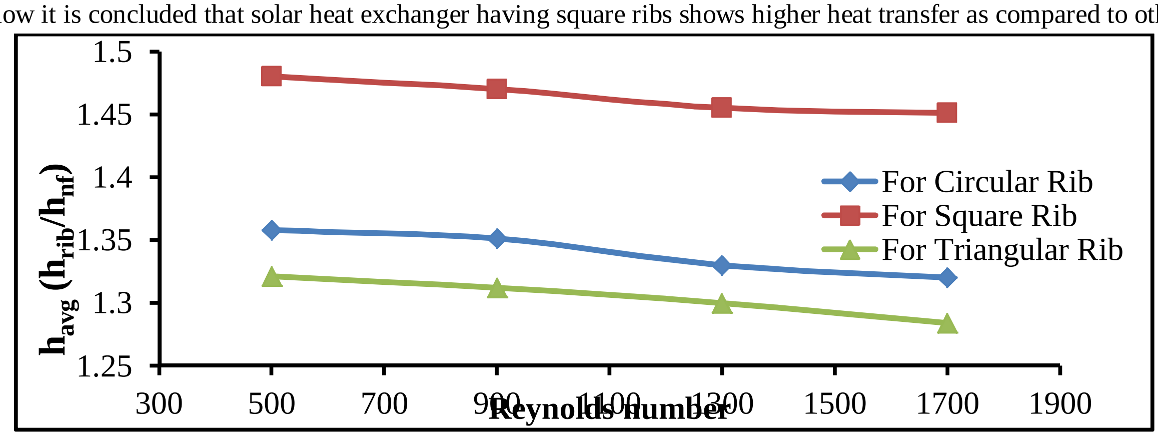

Fig.10 value of the average heat transfer coefficient ratio for a different rib with nanofluid as a working fluid

After analysing solar heat exchanger with different types of ribs for water and nano fluid as a working fluid, it calculate the percentage increment in heat transfer coefficient for nano fluid as compare to water as a working fluid.

Table.12 Shows percentage increment in heat transfer coefficient

S.No	Type of solar heat exchanger	Water as a working fluid	Nano fluid as a working fluid	Percentage (%)
1	Simple pipe	362	460	27
2	With Circular rib	501	625	24.7
3	With square rib	610	682	11.8
4	With triangular rib	478	608	27.19

V. CONCLUSION

From above analysis, it is found that the uses of ribs inside the solar heat exchanger increase the heat transfer. Through analysis, it is also found that the value of heat transfer coefficient increases with increase in Reynolds number, heat transfer coefficient is maximum for square shape rib in both the cases that are during using water and nanofluid as a working fluid. The average heat transfer coefficient ratio graph shows that rib used in the solar heat exchanger with nanofluid flow shows more heat transfer enhancement as compared to a solar heat exchanger with simple water flow. Overall it is found that square shape ribs show more heat transfer coefficient as compared to another rib.

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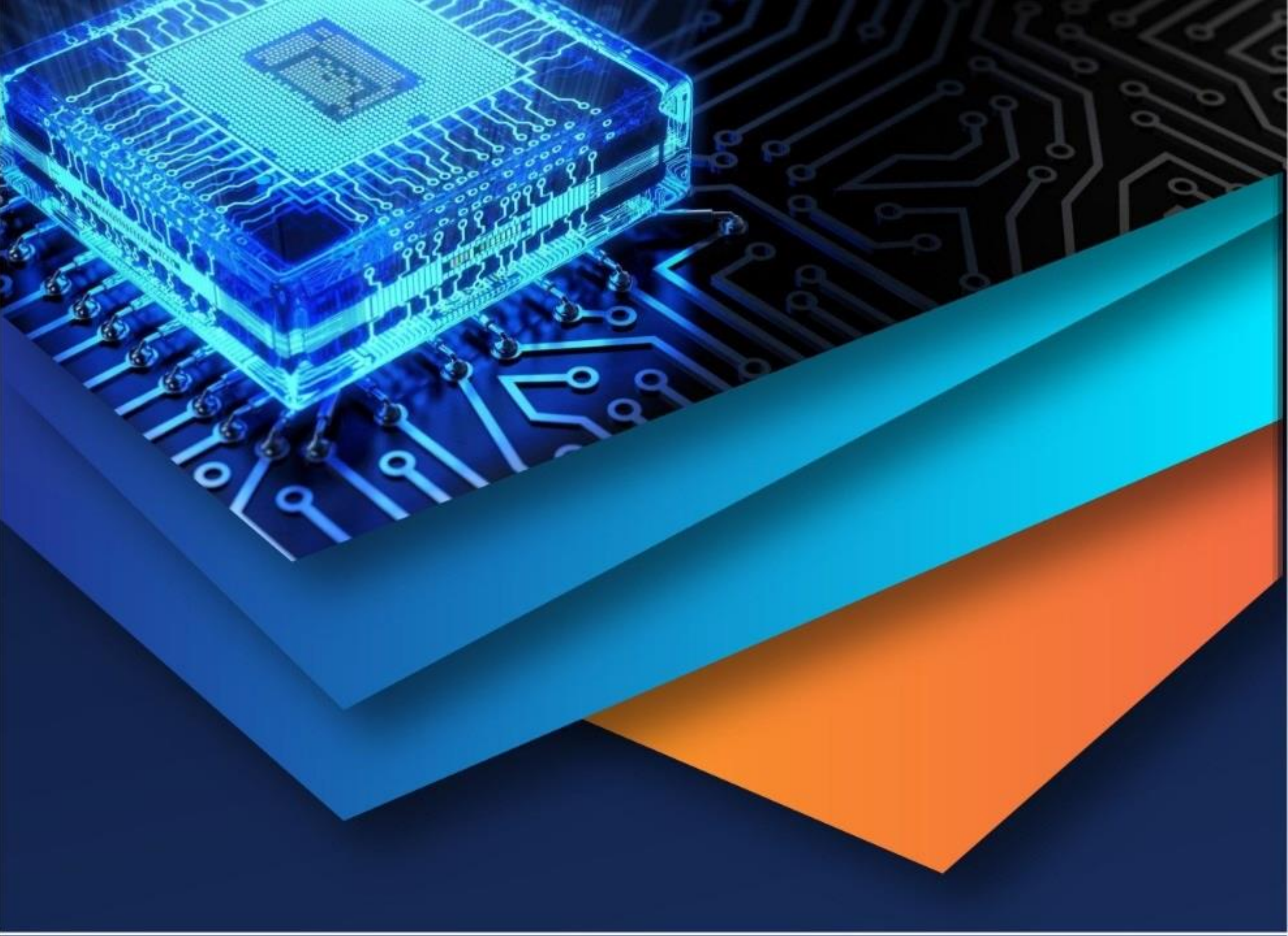

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