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Compare Results of Experimental With Cfd Analysis Using Diamond Shaped Roughness on the Absorber Plate of Solar Air Heater to Enhance Heat Transfer Coefficient

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ABSTRACT

An experimental investigation and CFD analysis has been compared to check the heat transfer characteristics in solar air heater by providing diamond shaped roughness on one broad wall of solar air heater. The roughened wall being heated while the remaining three walls are insulated. Low thermal efficiency generates by flat plate solar Air heater due to low thermal conductivity between Air and absorber plate.it is compulsory to enhance the thermal conductivity between air and absorber plate. Higher temperature generate in absorber plate causes maximum thermal losses dissipate to environment .It can be made possible by creating artificial roughness on absorber plate.so many number of parameters they can enhance the thermal conductivity such as relative roughness pitch (p/e) varies between 10-25 mm, the relative roughness height (e/Dh) = 0.023, Rib height (e) = 1mm, Duct aspect ratio (W/H) = 8:1, rate of air flow relate to Reynolds no.(Re) ranging from 3000-14000. Electric heater is used to heat the plate in indoor experiment. Absorber plate heated with the Electric heater while three walls insulated with thermocol sheet. Finally compare the effect of parameters on the heat transfer .Also compared the result of smooth duct under similar flow conditions with CFD analysis.

KEYWORDS Solar air heater; Diamond shaped rib; Heat transfer enhancement ;Duct aspect ratio; relative roughness pitch; Rib height;ANSYS Software

INTRODUCTION

Thermal conductivity of air can be enhanced by developing roughened surface on the absorber plate. Many investigators created artificial roughness in various forms to enhance the heat transfer coefficient. Creation of artificial roughness helps to produce turbulence near the wall to break the viscous sub layer which enhances the heat transfer between the absorber plate and air of solar heater. The artificial roughness is a technique to enhance the rate of heat transfer to the fluid flowing in a duct. The use of fine wires and ribs of different shapes creates artificial roughness that has been recommended to enhance the heat transfer coefficient by many investigators [3–16]. It would result in an increase in frictional losses this causes more power required by blower. To keep the friction losses at a minimum level, the turbulence must be creating very close to the duct surface. The ribs break the laminar sub-layer and create local wall turbulence due to flow separation and reattachment between consecutive ribs, which reduce the thermal resistance and enhance the heat transfer. There are many methods to produce roughness such as sand blasting, machining, casting, forming, welding or fixing ribs of small diameter wires. Nikuradse [1], Dipprey and Sabersky [2] developed a friction similarity law and a heat momentum transfer analogy for flow in rough tubes. It has been observed by several investigators that providing artificial roughness on the underside of absorber plate could enhance the heat transfer capability of a solar air heater. The main application of solar air heaters are space heating, seasoning of timber, curing of industrial products and these can also be effectively used for drying of

Nomenclature	
C_p	specific heat of air, J/kg k
D	equivalent or hydraulic diameter of duct, mm
e	rib height, mm
H	depth of duct, mm
h	heat transfer coefficient, W/m2k
I	intensity of solar radiation, W/m2
k	thermal conductivity of air, W/m k
L	length of duct, mm
m	mass flow rate, kg/s
P	pitch, mm
q	heat flux, W/m2
T	air temperature, K
T_a	ambient temperature, K
T_{am}	mean air temperature, K
T_i	air inlet temperature, K
To	air outlet temperature, K
T_{pm}	mean plate temperature, K
T_w	wall temperature, K
u	air flow velocity in the x direction, m/s
v	air flow velocity in the y direction, m/s
W	width of duct, mm
D_p	pressure drop, Pa

Dimensionless parameters	
B/S	relative roughness length
d/w	relative gap position
e/D	relative roughness height
e/H	rib to channel height ratio
f	friction factor
fr	friction factor for rough surface
Nu	Nusselt number
Nur	Nusselt number for rough duct
Nus	Nusselt number for smooth duct
P/e	relative roughness pitch
Pr	Prandtl number
Re	Reynolds number
St	Stanton number
W/H	duct aspect ratio
Greek symbols	
a	angle of attack, degree
d	transition sub-layer thickness, mm

e	dissipation rate, m2/s3
ρ	density of air, kg/m3

Concrete/clay building components. Prasad and Saini [3] investigated the effect of relative roughness height (e/Dh) and relative roughness pitch (p/e) on heat transfer and friction factor using circular wire roughness. It has been observed that increase in the relative roughness height results in a decrease of the rate of heat transfer enhancement although the rate of increase of friction factor increases. Increase in the relative roughness pitch results in a decrease in the rate of both heat transfer and friction factor. Gupta et al. [4] investigated the effect of relative roughness height, angle of attack and Reynolds number on heat transfer and friction factor in rectangular duct having circular wire ribs on the absorber plate. It was found that the heat transfer coefficient in roughened duct could be improved. The friction factor improves and increases by a factor up to 2.7 times of smooth duct. The maximum heat transfer coefficient and friction factor were found at an angle of attack of 60° and 70° respectively. Saini and Saini [5] experimentally investigated the effect of expanded metal mesh geometry on the heat transfer coefficient and friction factor in a large aspect ratio in rectangular duct. The maximum values of Nusselt number and friction factor founds corresponds to angle of attack values of 61.9 and 72.Verma and Prasad [6] had investigated the effect of similar geometrical parameters of circular wire ribs on heat transfer and friction factor. It was observed that the value of heat transfer enhancement factor (Nur/Nus) varies from 1.25 to 2.08 within the range of parameters investigated. Muluwork et al. [7] compared the thermal performance of staggered discrete V-apex up and down with Flat plate solar air heaters are used to heat air. [4, 6, 8] created Artificial roughened absorber plates of solar air heater as transverse wedge shaped rib, 90 degree broken transverse ribs, W-shaped ribs and circular wire rib roughness respectively. [8, 9] used fine wires as a rib to create artificial roughness on surface of different shapes to enhance heat transfer coefficient. This also increased the frictional losses which thereafter resulted in consumption of more power to run the blower. This paper aims to minimize friction losses .This friction losses create at a region very near to the duct surface. This region known as a laminar sub layer. Laminar sub-layer breaks by the ribs. This rib creates local wall turbulence which develops flow separation also reattachment developed between consecutive ribs, Reduction of the thermal resistance and enhancement of the heat transfer caused by reattachment between consecutive ribs. [2] Investigated the effect of relative roughness height (e/Dh) and relative roughness pitch (p/e) on heat transfer and friction factor using circular wire as roughness. It has been observed that increase in the relative roughness height results in a decrease of the rate of heat transfer enhancement and increase in the rate of friction factor. Rate of heat transfer and friction factor decreases if the relative roughness pitch increases. The Result of maximum enhancement in Nusselt number and friction factor occurs as 2.38 and 4.25 times than that of smooth duct, respectively.[3] Works on the effect of relative roughness height (e/Dh), angle of attack (α) and Reynolds number (Re) on heat transfer and friction factor in rectangular duct with circular wire as ribs on the absorber plate. Heat transfer coefficient can be improved by a factor up to 1.8.Conventional techniques are very expensive and time consuming to use for design and development of an artificially roughened solar air heater. Now a day Computational fluid dynamics (CFD) approach has emerged due to cost effective and obtained fast solution to design and optimization of an artificially roughened solar air heater. CFD is a design tool that continually developed. The goals of CFD are to be able to accurately predict fluid flow, heat transfer and chemical reactions in complex systems.CFD uses numerical methods and algorithms to solve and analyse problems that involve fluid flows. High speed computers are used to perform the calculations required to simulate the interaction of gases and liquids with surfaces defined by boundary conditions. With the help of high speed computers better solutions of fluid flow problem has been achieved. Researchers use this software that improves the speed and accuracy of complex simulation as well as turbulent flows. Literature search in the area of artificially roughened solar air heater and fond that very few CFD investigation of artificially roughened solar air heater has been done to evaluate the optimum rib shape and configuration, which can enhance convective heat transfer with minimum pumping power requirement.Chaube et al. [18] conducted two dimensional CFD based analysis of an artificially roughened solar air heater having ten different ribs shapes viz. rectangular, square, chamfered, triangular, etc. Provided on the absorber plate. CFD code, FLUENT 6.1 and SST k–x turbulence model were used to simulate turbulent airflow. The best performance was found with rectangular rib of size 3 - 5 mm and CFD simulation results were found to be in good agreement with existing experimental results. Kumar and Saini [19] performed three dimensional CFD based analysis of an artificially roughened solar air heater having arc shaped artificial roughness on the absorber plate. FLUENT 6.3.26 commercial CFD code and Renormalization group (RNG) k–e turbulence model were employed to simulate the fluid flow and heat transfer. Over all enhancement ratio with a maximum value of 1.7 was obtained and results of the simulation were successfully validated with experimental results. Karmare and Tikekar [20] carried out CFD investigation of an artificially roughened solar air heater having metal grit ribs as roughness elements on the absorber plate. Commercial CFD code FLUENT 6.2.16 and Standard k–e turbulence were employed in the simulation. Authors reported the absorber plate of square cross-section rib with 58° angle of attack was thermo hydraulically more efficient. Yadav and Bhagoria [21] carried out CFD investigation of an artificially roughened solar air heater having circular transverse wire rib roughness on the absorber plate. A two-dimensional CFD simulation was performed using ANSYS FLUENT12.1 code as a solver with RNG k–e turbulence model. Maximum value of thermal enhancement factor was reported to be1.65 for the range of parameters investigated. A CFD based study of conventional solar air heater was performed by Yadav and Bhagoria[22]. ANSYS FLUENT and RNG k–e turbulence model were used to analyze the nature of the flow. Results predicted by CFD were found to be in good agreement with existing empirical correlation results. Yadav and Bhagoria [23] conducted a numerical analysis of the heat transfer and flow friction characteristics in an artificially roughened solar air heater having square section transverse ribs roughness considered at underside of the top heated wall. The thermo-hydraulic performance parameter under the same pumping power constraint was calculated in order to examine the overall effect of the relative roughness pitch. The maximum value of thermo-hydraulic performance para meter was found to be 1.82 corresponding to relative roughness pitch of 10.71. Yadav and Bhagoria [24] carried out a numerical investigation of turbulent flows through a solar air heater roughened with semi-circular sectioned transverse rib roughness o the absorber plate. The physical problem was represented mathematically by a set of governing equations, and the transport equations were solved using the finite element method. The numerical results showed that the flow-field, average Nusselt number, and average friction factor are strongly dependent on the relative roughness height. The thermo-hydraulic performance parameter was found to be the maximum for the relative roughness height of 0.042.Yadav and Bhagoria [25] performed a CFD based investigation of turbulent flows through a solar air heater roughened with square sectioned transverse rib roughness. Three different values of rib pitch (P) and rib-height (e) were taken such that the relative roughness pitch (p/e = 14.29) remains constant. The relative roughness height, e/D, varies from 0.021 to 0.06 and Reynolds number, Re, varies from 3800 to 18,000. The results predicted by CFD showed that the average heat transfer, average flow friction and thermo hydraulic performance parameter were strongly dependent on the relative roughness height. A maximum value of thermo hydraulic performance parameter was found to be 1.8 for the range of parameters investigated. Yadav and Bhagoria [26] employed circular sectioned rib roughness on the absorber plate to predict heat transfer and fluid friction behavior of an artificially roughened solar air heater by adopting CFD approach. ANSYS FLUENT 12.1 and RNG k–e turbulence model were employed in their simulation. The maximum average Nusselt number ratio and friction factor ratio are found to be 2.31 and 3.14, respectively for the investigated range of parameters.

2. INDOOR EXPERIMENT PROGRAM

2.1 Experimental apparatus

An indoor experimental set up consist with some parts such as duct which is divided in to four parts inlet section ,test section, mixing section ,and exit section. Here (W) Width and (H) height of the duct .length of inlet section is 177 mm , test section 1500 mm (33.75 Dh), mixing section and exit section 354mm along with 87mm baffles spacing. A blower is used to suck fluid (air) that operates on three phase 240 Volts, other parts also used to control flow of fluid such as control valve, orifice plate and other devices. Some equipment also used to measure values related with calculation such as milivoltmeter, micro manometer to measure pressure head for Reynolds no. as referred with (ASHRE 1977) and inclined manometer for pressure measurement. A roughened G.I absorber plate of length 1500 mm long have roughness of diamond shape placed on the top of the test section. Several numbers of thermocouples are fixed in roughened plate as shown in fig-1. Mixing section is provided before exit section. Length of this section i.e. 345 mm in length. The objective behind providing the exit section was to reach the end effect in the last section .three baffles at 87 mm distance are provided to mix the hot air coming from the duct.

Figure shows the position of thermocouples in setup

Fig-1

Figure of experimental setup

Fig-2

Control valve is also provided beside the orifice that controls the air coming from orifice. That control valve varies the Reynolds number. The experimental setup covered with thermocol sheet that avoids the exchanges heat from inside to outside and vice versa. On one side of the G.I. sheet prepared by pasting diamond shape ribs and other side thermocouples is fixed and painted by a black paint. The calibrated copper- constantan 0.3 mm (24 SWG) thermocouples were used to measure the temperature of air and the heated plate at different locations. The position of thermocouples on the black painted wall is shown in Fig-1. The roughened G.I. sheet placed at a height of 25 mm on the duct .Flat plate heater of size 1500 mm x 200 mm is placed over the G.I roughened plate. Voltmeter and Ammeter are connected with the heater through main supply. Calibrated copper–constantan thermocouples are used to measure temperature .these thermocouples are affixed on the black side of the sheet. Inclined manometer is used to measure mass flow rate .inclined manometer is connect across the orifice plate. Mass flow rate can be varied with the help of control valve. [12], [13] reported the optimum value of p/e for the rectangular ducts to be10. [12], [13], [14] have reported an optimum rib angle of 45° to 60°. The length of the circular GI pipe provided was based on pipe diameter d1, which is a minimum of 10 d1 on the upstream side and 5 d1 on the downstream side of the orifice plate. In the present experimental set-up, we used 1000 mm (13 d1) pipe length on the upstream side and 700 mm (9 d1) on the downstream side.

2.2 Absorber plates

Fig -3,fig-4 and fig-5 shows the geometry of roughness plate. Presently we are comparing the result of experimental performance and CFD analysis with diamond shape ribs as an artificial roughness. This roughness is created by pasting diamond shape rib on mild steel. The height of rib (e) =1mm and pitch (p) =10mm to 25mm.After reaching the steady state condition note down the heater assembly voltage and current, the plate temperatures, the inlet and exit air temperatures and the pressure drop across the duct and across the orifice plate .

TABLE 1
EXPERIMENTAL CONDITION

Parameter	Values
Reynolds number(Re)	3000 – 14,000
Channel aspect ratio(W/H)	8.0
Test length (L)mm	1500
Roughness height(e)mm	1mm
Relative roughness height (e/ Dh)	0.023 and 0.034
Hydraulic Diameter(Dh)mm	44.44
Roughness pitch(P)mm	10,15,20 and 25
Insulation(I) W/m2	900-1000

Roughened plate of different pitches

Fig-3

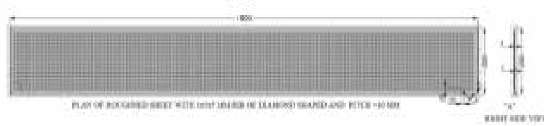


Fig-4

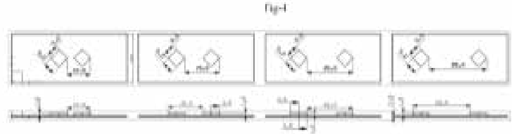


Figure shows variation of pitches, rib height and pattern of rib

2.3 Experimental procedure

An experimental setup consist of all instruments were connected well and placed for proper operation. All The joints are checked with soap bubble technique so that air leakage may be detected by switching on the blower. Micro manometer and inclined U-tube manometer is connected to measure pressure and friction factor respectively. Blower is switched on and the flow of air controlled by control valve. The quasi-steady state condition is occurring if the temperature at a point does not change for about 10-12 minutes. All runs of reading takes approximately 40-50 minutes for quasi-steady state condition. To change the Reynolds no. the flow rate of Air is changed with the help of control valve. The temperatures of air at entering the duct, leaving the duct were recorded. Heating plate reading may be taken with the help of thermocouples in the form of millivolt-meter. Millivolt-meter readings are converted into temperatures. After the steady state has reached, all the readings such as voltage and current, the plate temperatures, the inlet and exit air temperatures and the pressure drop across the duct and across the orifice plate have been recorded. For each roughness sheet 07 runs have been conducted at air-flow rates corresponding to the flow Reynolds numbers between 3000 and 14000.

The following parameters were measured during the experiments

1. Pressure drop across the orifice plate by inclined U- tube manometer
2. Pressure drop across the duct by using micro manometer.
3. Inlet air temperature of collectors by using digital milivoltmeter and thermocouples.
4. Outlet air temperature of collectors
5. Temperature of plate

2.4 VALIDATION TEST

Validation curve with smooth plate is taken by S.S.Pawar et al. [27] and the value of Nussselt no. and friction factor is obtained from experimental data .These data is compared with value of Dittus Boelter and modified Blasius equation respectively.

DittusBoelter equation

$$Nus = 0.024\ Re^{0.8}\ Pr^{0.4} \qquad (1)$$

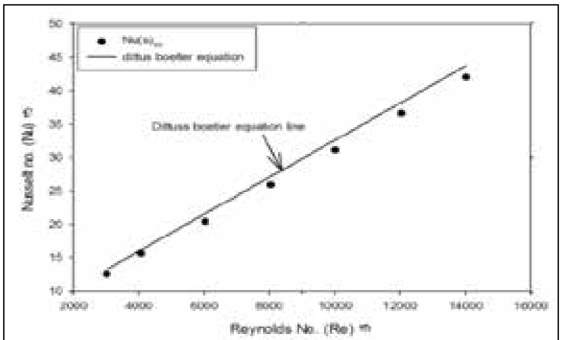
Modified Blasius equation

$$fs = 0.085\ Re^{-0.25} \qquad (2)$$

2.5 VARIATION OF TEMPERATURE ALONG TEST DUCT

Experimental wooden duct have air entering section, test section, mixing section and exit section. Atmospherically air enters at room temperature in the entering section and absorbs heat in the test section.

Complete air of the duct mixes in the mixing section and finally exits from the exit section. Temperatures of all the four sections are noted down and are plotted as shown in graph 1.



Validation graph between standard Nusselt for smooth plate & Experimental value for smooth plate

Graph-1

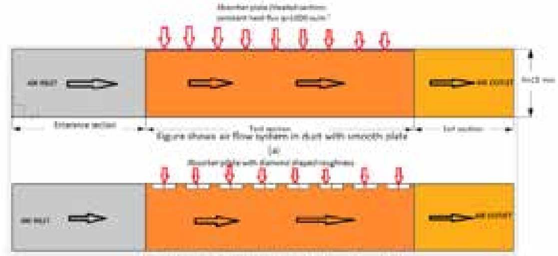


Fig-4 (a) Shows air flow in duct with smooth plate
(b) Shows air flow in duct with roughened plate

3. Data Reduction

3.1 Mean Air & Plate Temperature

Tile mean air temperature or average flow temperature flow is the simple arithmetic mean of the measure values at the inlet and exit of the test section. Thus

$$T_{fav} = \frac{t_i + t_{oav}}{2}$$

The mean plate temperature, tpav is the weighted average of the reading of 6 points located on the absorber plate.

3.2 Pressure Drop Calculation

Pressure drop measurement across the orifice plate by using the following relationship:

ΔPo= Δh x 9.81 x ρm x 1/5

Where

ΔPo = Pressure diff.

ρm = Density of the fluid (Mercury) i.e. 13.6x103

Δh = Difference of liquid head in U-tube manometer, m

3.3 Mass Flow Measurement

Mass flow rate of air has been determined from pressure drop measurement across the orifice plate by using the following relationship:

Where $$m = C_d \times A_o \times P_o \left[\frac{2\rho\Delta P_o}{(1-\beta^4)^{0.5}}\right]$$

m = Mass flow rate, kg / sec.

C_d = Coefficient of discharge of orifice i.e. 0.62

A_0 = Area of orifice plate, m2

P_o = Density of air in Kg/m3

β = Ratio of dia. (do / dp) i.e. 26.5/53 = 0.5

3.4 VELOCITY MEASUREMENT*:*

$$V = \frac{m}{\rho WH}$$

Where,

m = Mass flow rate, kg / sec

ρ = Density of air in Kg/m3

H = Height of the duct in m

W = Width of the duct, m

3.5 REYNOLDS NUMBER

The Reynolds number for flow of air in the duct is calculated from:

$$R_e = \frac{VD}{v}$$

Where,

v = Kinematics viscosity of air at t_{fav} in m 2/sec

$$D_h = \frac{4WH}{2(W+H)}$$

3.6 Heat Transfer Coefficient
Heat transfer rate, Qa to the air is given by:

$$Q_a = mC_p(t_o - t_i)$$

The heat transfer coefficient for the heated test section has been calculated from:

$$h = \frac{Q_a}{A_{p(t_{pav} - t_{fav})}}$$

A_p is the heat transfer area assumed to be the corresponding smooth plate area.

3.7 NUSSELT NUMBER
Tile Heat Transfer Coefficient has been used to determine the Nusselt number defined as;

$$(Nu) = \frac{hD_h}{K}$$

Where k is the thermal conductivity of the air at the mean air temperature and D_h is the hydraulic diameter based on entire wetted parameter.

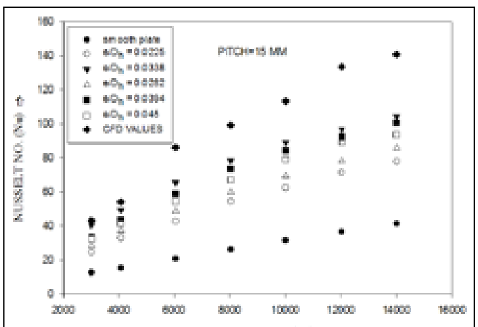
3.8 THERMAL EFFICIENCY
The Thermal Efficiency for test section is calculated from:

Thermal efficiency (η) = Q_a / ApI

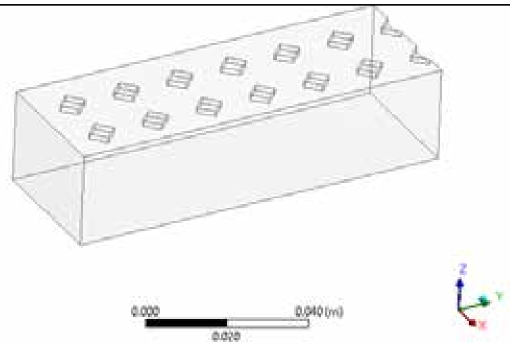
$$(\eta) = \frac{Q_a}{A_p I}$$

Where, I = Heat Flux i.e. 1000 W/m2

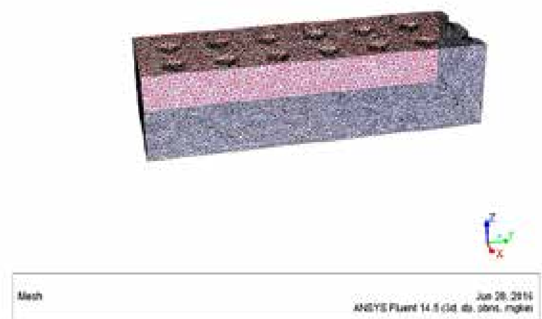
4. RESULTS AND DISCUSSION
Heat transfer coefficient and friction factor compared roughened plate with smooth plate under similar fluid flow condition. Roughness creates by pasting regular diamond shaped rib to see the enhancement in heat transfer coefficient. Fig.3 shows the roughened plate of different pitches. Fig-4 and fig-5 shows the geometry of roughened plate. These graph shows as Nusselt number increases with increases in Reynolds numbers. Comparison of experimental1mm diamond shaped rib height with the results of CFD of same parameter as experimental. The Nusselt number found maximum at the pitch value of 15mm with Rib height 1mm.Also indicate that heat transfer coefficient is maximum at 15 mm pitch roughened plate. It is nothing but the ratio of conductive resistance to convective resistance of heat flow and as Reynolds number increases thickness of boundary layer decreases and hence convective resistance decreases which in term increases the Nusselt number.



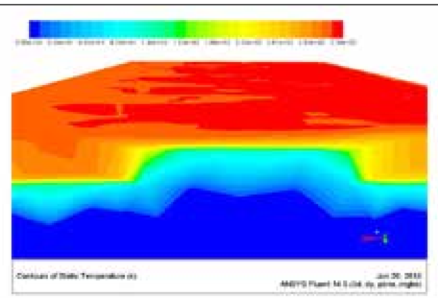
GRAPH BETWEEN (Re V/S Nu)FOR ANALYTICAL AND CFD VALUES
GRAPH NO.2



CAD MODEL
FIG-7



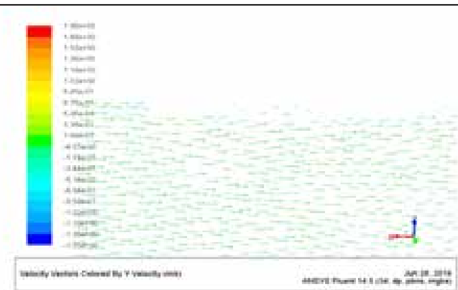
MESH MODEL
FIG-8



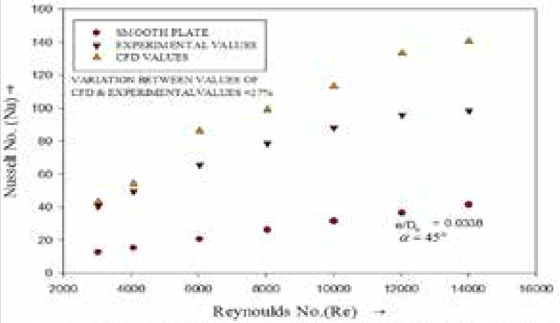
TEMPERATURE VARIATION WITH TOP WALL

IN ABOVE FIGURE COLOUR INDICATES TEMPERATURE AT A REGION.ACCORDING TO COLOUR-
TOP WALL TEMPERATURE= 3.26e+2
MID TEMPERATURE= 1.96e+2
LOWEST TEMPERATURE= 1.75e+2

FIG-9

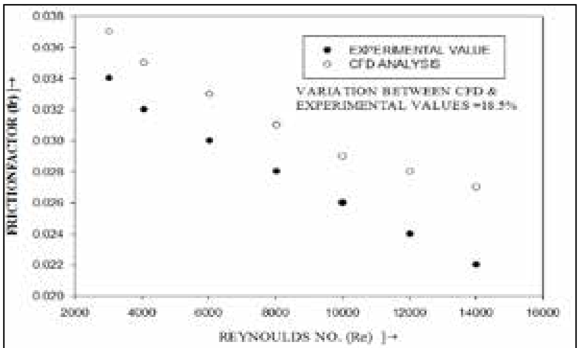


VELOCITY STREAMLINE
FIG-10



EFFECT OF REYNOULDS NO. (Re) ON NUSSELT ON (Nu) FOR RELATIVE ROUGHNESS HEIGHT OF 0.0338 RIB HEIGHT AND FOR GIVEN ANGLE OF ATTACK OF FLOW FOR DIAMOND SHAPED RIB

GRAPH-3



COMPARISION IN VALUES OF FRICTION FACTOR (fr) OF EXPERIMENTAL WITH CFD ANALYSIS FOR RELATIVE ROUGHNESS HEIGHT (e/D_h)=0.0338 AND RELATIVE ROUGHNESS PITCH (p/e) = 10

GRAPH-4

5. CONCLUSION

The major conclusions of this article are as follows:

1. Presence of diamond shaped rib on the absorber plate is an effective technique to enhance the rate of heat transfer as compared to the smooth solar air heaters also compares results with CFD analysis.
2. The Nusselt no. (Nu) and friction factor (fr) are strongly dependent on the relative roughness pitch (p/e) and relative roughness height (e/Dh) of diamond shaped rib together with the flow Reynolds number.
3. It has been found that Nu increases with the increase in Re.
4. Maximum value of Nusselt no. (Nu) has been found to be 78.24.
5. It has been found that friction factor (f r) decreases with the increase in Reynolds no. (Re)
6. Maximum value of friction factor (f r) has been found to be 0.034.
7. Values of Nusselt no.(Nu) generated by CFD analyses process is 27% more than experimental values.
8. Values of Friction factor (fr) generated by CFD analyses process is 18.5% more than experimental values.

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