Experimental Investigation of Heat Transfer and Friction Factor inSolar Air Heater Ductusing Discrete Arc Shaped Rib Roughness on Absorber Plate

M. M. Sahu
Research Scholar,
Mechanical Engineering Department,
M.A.N.I.T.Bhopal
(M.P.)462051, India

Dr. J. L. Bhagoria
Professor,
Mechanical Engineering Department,
M.A.N.I.T.Bhopal
(M.P.)462051, India

***Abstract*---Solar air heater is used for heating air for several purposes due to itssimplicity and low maintenance. Low thermal efficiency between air and absorber plate can be increased by creating artificial roughness on absorber plate. In present work an experimental investigation has been carried out to study the heat transfer coefficient and friction factor by using discrete arc shaped ribs on absorber plate of a solar air heater, the roughened wall being heated while the remaining three walls are insulated. The roughened wall has roughness with pitch (P) ranging from 10mm to 20 mm,height of the rib in the range of 1-2 mm,relative roughness pitch (P/e) =10, angle of arc 30°,relative angle of attack (α/90) 0.3333, and duct aspect ratio(W/H)=8,. The air flow rate corresponds to Reynolds number in the range 3000-14000. The experimental results have been compared with those for smooth duct under similar flow and thermal boundary conditions to determine the thermal efficiency of solar air heater.**

Key words: Solar air heater, absorber plate, artificial roughness, discrete arc shaped ribs, pitch, Reynolds number, heat transfer coefficient and friction factor.

INTRODUCTION

Solar air heater is a solar thermal system which is used for heating the air . Solar Air heaters due to their simple in design, are cheap and most widely used for heating air. The main application of solar air heaters are space heating, seasoning of timber ,drying of agro and allied products, food items such as fruits, vegetables, chillies, tea-leaves, fish, salt, etc. The solar air heater can be used in many industrial activities (drying/heating) such as chemical, pharmaceutical, limited areas of textiles and hosieries, tannery, edible oil, etc;A conventional air heater is typically a rectangular flat passage between two parallel smooth plates. The air to be heated is passed through a rectangular cross-section duct below a metal absorber plate with the sun-facing side blackened to facilitateabsorption of solar radiation incident on the absorber plate. Transparent covers are placed over the absorber plate to reducethe thermal losses from the heated absorber plate. A solar air heater is simple in design and requires littlemaintenance. [13] The thermal performance of conventional solar air heater has been found to be poor because of the low convective heat transfer coefficient from the absorber plate to the air (Duffie and Beckman 1980). Thermal efficiency of air heater can be improved by developing roughened surface on the absorber plate. An artificial roughness on the heat transfer surface in the form of wires or ribs of various geometrical shapes mainly creates turbulence near the wall or breaks the laminar sub-layer and thus enhances the heat transfer coefficient with a pressure loss penalty. In order to keep the friction losses at a low level, the turbulence must be created only in the region very close to the duct surface, i.e. in the laminar sub-layer. The application of artificial roughness in the form of fine wires or ribs of different geometries on the heat transfer surface has been recommended to enhance the heat transfer coefficient by several investigators using experimental and computational fluid dynamics (CFD). Many investigators created artificial roughness in various forms to increase the heat transfer coefficient. [12] 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. [4,5,6] 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. [6, 7] 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.[14] Complete information about different experimental studies on solar air heater may be found in excellent review papers by Hans et al. [8], Bhushan and Singh [9] and Kumar et al. [11].

INDOOR EXPERIMENTAL SET-UP

The schematic diagramofexperimental set-up including the test section is shown in Fig. 4.1. The ·flow system consists of an entry section, a test section, an exit section, a flow meter and a centrifugal blower. The duct is

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

of size 2042mm x 200 mmX20mm (dimension of inner cross-section) and is constructed from wooden panels of 25 mm thickness. The test section is of length 1500mm (33.75 D_h). The entry and exit lengths were 192 mm (7.2 D_h) and 350 mm (12 D_h), respectively. A short entrance length (L/Dh=7.2) was chosen because for a roughened duct the thermally fully developed flow is established in a short length 2-3 hydraulic diameter [22]. For the turbulent flow regime, ASHRAE standard 93-77 [22] recommends entry and exit length of $5\sqrt{WH}$and $2.5\sqrt{WH}$, respectively.

In the exit section after 116 mm, three equally spaced baffles are provided in a87 mm length for the purpose of mixing the hot air coming out of solar air duct to obtain a uniform temperature of air (bulk mean temperature) at the outlet.

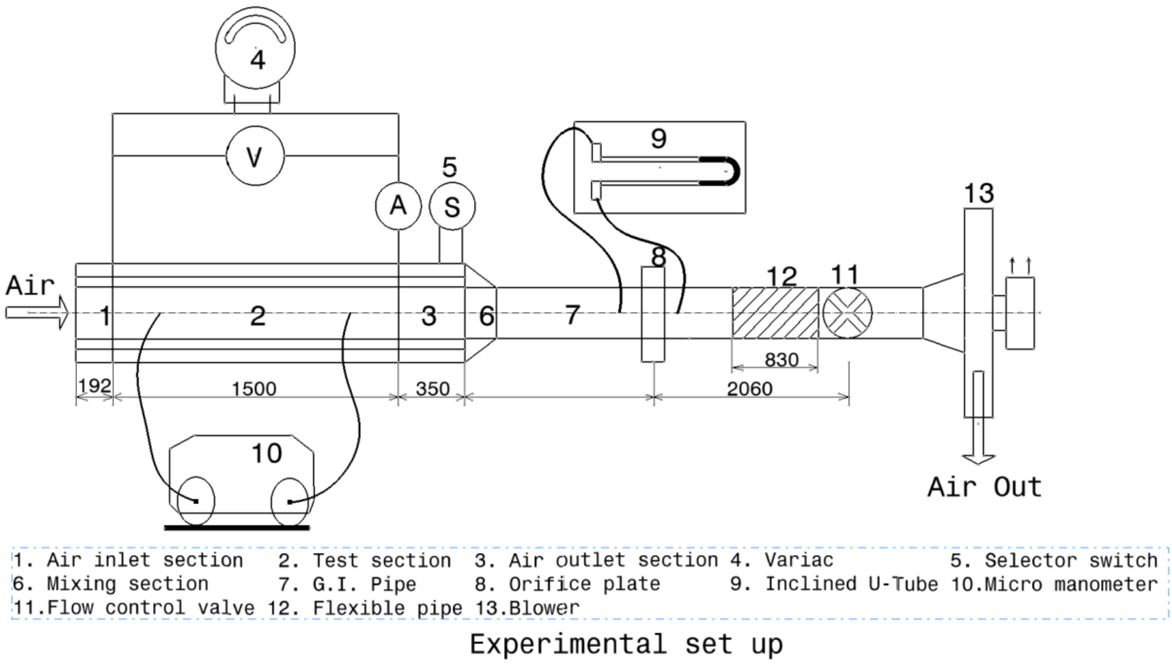

Fig. 1 Schematic diagram showing top view of experimental Setup

An electric heater is provided for heating absorber plate.The heat flux may be varied from 0 to 1000 W/m^2 by a variac across it.

The outside of the entire set-up, from the inlet to the orifice plate, is insulated with thick thermocol sheet having a very low thermal conductivity. The heated plate is a 1 mm thick GI plate with integral rib-roughness formed on its rear side and this forms the top broad wall of the duct, while the bottom wall is formed by 25 mm wood with insulation below it. The top sides of the entry and exit sections of the duct are covered with smooth faced 8 mm thick plywood.

The mass flow rate of air is measured by means of a calibrated orifice meter connected with an inclined manometer, and the flow is controlled by the control valves provided in the lines. The orifice plate has been designed for the flow measurement in the pipe of inner diameter of 53 mm, as per the recommendation of Preobrazhensky [23]. The orifice plate is fitted between the flanges, so aligned that it remains concentric with the pipe.

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 as recommended by Ehlinger [24].

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. The calibrated copper-constantan 0.3 mm (24 SWG) thermocouples were used to measure the air and the heated plate temperatures at different locations.A digital micro voltmeter is used to indicate the output of the thermocouples in ^{0}C. The temperature measurement system is calibrated to yield temperature values (t±0.1)^{0}C. The pressure drop across the test section was measured by a micro-manometer.

It is an open flow loop that consists of a test duct with entrance & exit sections, a blower, control valve, orifice plate and various devices for measurement of temperature & fluid head.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

Table 1 Experimental parameters for investigation

Parameter	Values
Reynolds number	3000-14000
Relative roughness height (e/D_h)	0.0225 – 0.045
Relative roughness pitch(P/e)	10
Thickness of plate	1 mm
Channel aspect ratio (W/H)	8
Test length	1500 mm
Hydraulic diameter	44.44 mm

Absorber Plate----G. I. sheet of 1 mm thickness is used for absorber plate. Absorber plate prepared by 1 mm thick G. I. sheet of 1500 mm length and 210 width. Roughness on the absorber plate created by pasting circular copper wire of 1 mm, 1.5 mm and 2 mm diameter in arc shape at different pitches 10 mm, 15 mm and 20 mm. The full length of arc is considered B, arc is broken in different length segment B/2,B/3,B/4 and B/5. The geometry of roughness is show in fig.4. Figure 3 shows the actual photograph of rough absorber plate. Roughness is created on one side of absorber plate while the other side remains plane and it painted by black paint also affixed thermocouples on this side.

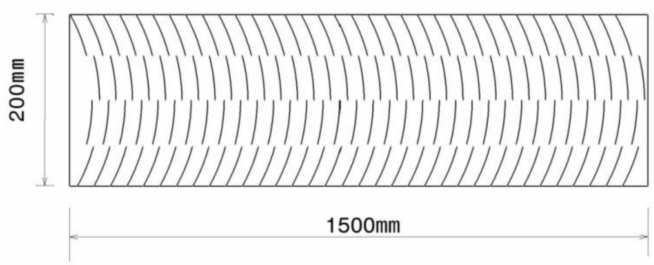

Fig.2 Schematicdiagram of absorber plate

Fig.3 Actual photograph of absorber plate of different pitches

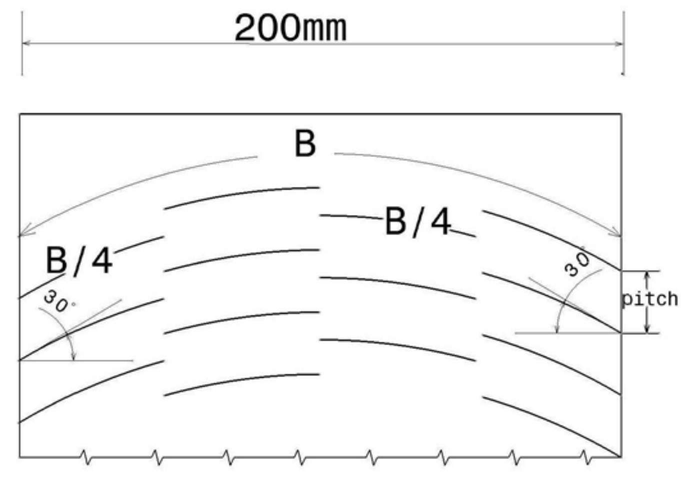

Fig.4 Geometry of roughness

EXPERIMENTAL PROCEDURE

All components of the experimental set up and the instruments have been checked for proper working before starting the setup. Also check all connections of instruments in proper way and correct. The blower is then switched on and the joints of the setup are checked for air leakage with the help of soap bubble technique. Inclined U-tube manometer is used for measuring the flow of air in the duct. Micro manometer is used to measure pressure drop across the duct. Air flow can beadjusted with the help of control valve for desired value of the Reynolds number. There is an electric heater for heating the plates. A variac is attached with electric heater so the supply of electricity can be adjusted at desired value. After switching on the blower and heater wait for steady state condition reached. Collect the relevant data for each rib configuration at various Reynolds number 3000-14000. The following parameters are needed tobe measured during experiment.

a) Pressure drop across the orifice plate
b) Pressure drop across the duct
c) Temperature of air at inlet of collector
d) Temperature of air at outlet of collector
e) Temperature of plate

VALIDATION TEST

The value of Nusselt number and friction factor determined from experimental data for smooth duct have been compared with the values obtained from Dittus-Boelter Equation and Modified Blasius Equation for Nusselt number and friction factor respectively.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

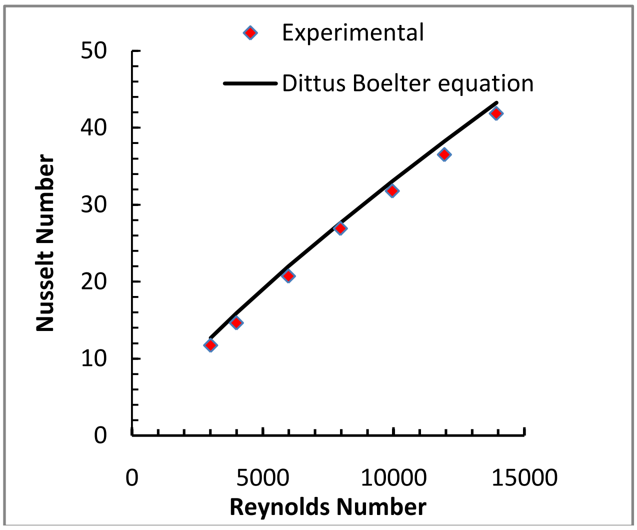

Fig.5 Graph between Reynolds Number and Nusselt Number

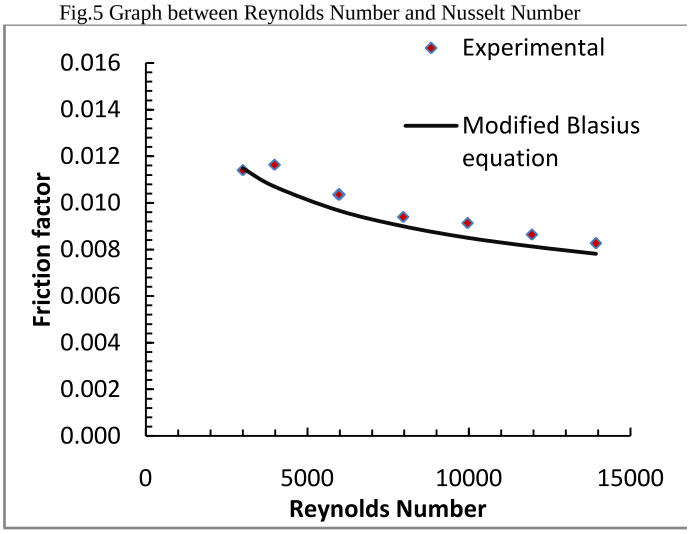

Fig.6 Graph between Reynolds Number and Friction factor

Data Reduction

Data analysis :Table 1 shows the experimental parameter.

Mean Air & Plate Temperature

The mean air temperature is the simple arithmetic mean of the measured values of air temperatures at the inlet and exit of the test section. Thus

$T_{fav}= (t_i+ t_{oav}) /2$

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

Pressure Drop Calculation

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

$\Delta Po = \Delta h \times 9.81 \times \rho_m \times 1/5$

Where

ΔPo = Pressure difference ρ_m = Density of the fluid (Mercury) i.e. $13.6x10^3$ Δh = Difference of liquid head in inclined U-tube manometer, m

Mass Flow Measurement

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

$m = C_d \times A_0 \times [2 \rho \Delta Po / (1 - \beta^4)]\ 0.5$

Where

m = Mass flow rate, kg / sec.

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

A_0 = Area of orifice plate, m^2

ρ= Density of air in Kg/m^3

β= Ratio of dia. (d_o / d_p) i.e. 26.5/53 = 0.5

Velocity Measurement:

$V = m / \rho WH$

Where,

m = Mass flow rate, kg / sec

ρ = Density of air in Kg/m^3

H = Height of the duct in m

W = Width of the duct, m

Reynolds Number

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

$Re= VD / \nu$

Where,

ν= Kinematics viscosity of air at t_{fav} in m^2/sec $D_h = 4WH / 2 (W+H) =0.04444$ m

Heat Transfer Coefficient

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

$Q_a = m\, c_p\, (t_o – t_i)$

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

$h = Q_a / A_p\, (t_{pav} - t_{fav})$

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

Nusselt Number

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

Nusselt No. (Nu) = $h D_h / k$

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

Thermal Efficiency

The Thermal efficiency for test section iscalculated from:

Thermal efficiency (η) = $Q_a / A_p\, I$

Where,

I = Heat Flux i.e. 900 W/m^2

RESULTS AND DISCUSSION

Heat transfer coefficient, friction factor and thermal efficiency compared roughened plate with smooth plate under similar fluid flow conditions. Roughness creates by pasting circular wire rib in discrete arc shape to seen the improvement in heat transfer coefficient.fig.3 shows the roughened plate of different pitches.fig.4 shows the geometry of roughened plate. Fig.9 shows effect of Reynolds Number on Nusselt number and fig.7 Shows effect of Reynolds Number on friction factor. Fig.8 shows effect of Reynolds Number on thermal efficiency.In this

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

experiment the arc shape rib discrete in 4 segment.The experiment is conducted for different pitch value 10 mm,15 mm and 20 mm,while the relative roughness pitch kept 10.It is found that the Nusselt number is maximum at the pitch value of 15 mm, thermal efficiency is also maximum at the pitch value of 15 mm and the value of friction factor is minimum at the pitch value of 15 mm.It is also found that as the Reynolds Number is increases the value of Nusselt Number and thermal efficiency increases while the friction factor decreases with increase in Reynolds Number.

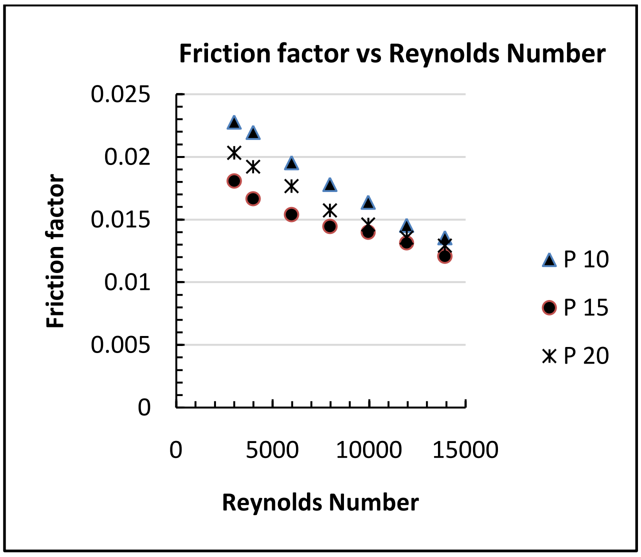

Fig.7 Reynolds Number vs Friction factor

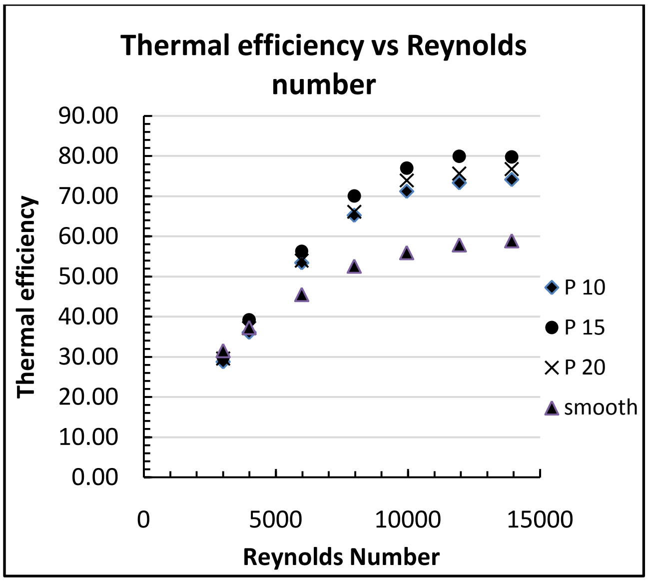

Fig.8Thermal efficiency vs. Reynolds number

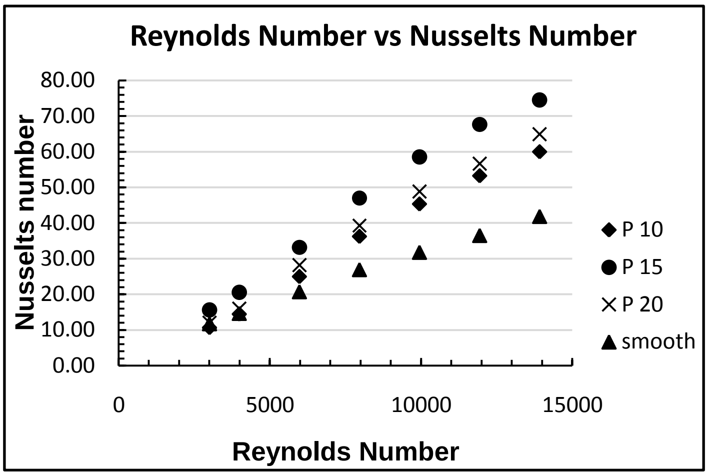

Fig.9 Reynolds Number vsNusselts Number

CONCLUSION

In the present work the discrete arc shape rib is used as artificial roughness on the undersides of a broad wall of solar air heater. Resultshave been compared with those of a smooth duct under similar flow conditions to determine enhancement in heat transfer coefficient and friction factor.The following conclusions have been drawn from this investigation.

1. It is found that the Nusselt Number increases as increases the Reynolds Number, attains a maximum for pitch of 15 mm. **2** At low Reynolds Number the value of Nusselt increases sharply and at higher value of Reynolds Number the value of NusseltNumber increases very slightly in comparison to low Reynolds Number .**3** It is also concluded that at low Reynolds Number a smooth duct gives better heat transfer than the artificial roughened duct. **4** The experimental values of the thermal efficiency of the roughened absorber plates tested have been compared with the smooth plate. A plate having roughness pitch 15 mm gives the highest efficiency of 79.99. **5** It is also found that at lower value of Reynolds Number the friction factor decreases sharply and becomes constant or decreases very slightly at higher value of Reynolds Number.

REFERENCES

[1] Ehlinger AH. Flow of air and gases. In: Salisbury JK, editor. Kent's Mechanical Engineers Hand- book, Power Volume. New York: Wiley, 1950:1.101.21.
[2] ASHARE Standard 93-97. Method of testing to determine the thermal performance of solar collectors, 1977.
[3] Preobrazhensky VP. Measurement and Instrumentation in Heat Engineering [English translation], vol. 2. Moscow: Mir Publisher, 1980.
[4] KarwaR ,Solanki SC and Saini JS “heat transfer coefficient and friction factor correlations for the transitional flow regime in rib roughened rectangular ducts.”Int.J.Heat Mass Transfer.42(9),1597-1615(1999)
[5] Bhagoria J.L. Heat transfer coefficient and fiction factor rectangular solar air Heater duct having transverse wedge shaped rib roughness on the absorber PlateInt j renewable Energy2002: 25: 341-69.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)

[6] M.M. Sahu, J.L. Bhagoria "Augmentation of heat transfer coefficient by using 90° broken transverse ribs on absorber plate of solar air heater" Renewable Energy, Volume 30, Issue 13, Pages 2057-2073, (2005).
[7] Saini R.P, Saini S.K, "Development of correlations for Nusselt number and friction factor for solar air heater with roughened duct having arc-shaped wire as artificial roughness" int. J solar Energy, article inpress(2008).
[8] Hans, V. S., Saini, R. P. and Saini, J. S. "Performance of Artificially Roughened Solar Air Heaters- A Review",Renewable and SustainableEnergy Reviews, Vol. 13, 2009, pp. 1854–69.
[9] Bhushan, B. and Singh, R. "A Review on Methodology of Artificial Roughness used in Duct of Solar Air Heaters",Energy, Vol. 35, 2010, pp. 202–12.
[10] A.M.Lanjewar, J.L.Bhagoria and R.M.Sarviy"Heat transfer enhancement in solar air heater", Indian Journal of Science and Technology, Vol.3, No.8,(Aug 2010),pp.908-910.
[11] Kumar, A., Saini, R. P. and Saini, J. S. "Heat and Fluid Flow Characteristics of Roughened Solar Air Heater Ducts- A Review",RenewableEnergy, Vol. 47, 2012, pp. 77-94.
[12] Pawar S.S., HindoliaD.A, Bhagoria J.L. "Enhancement of heat transfer coefficient using Diamond shaped roughness on the absorber plate of solar air heater" International journal of engineering research and application Vol.-2, Issue -3, March-April 2013; pp-968-974.
[13] YadavAS,BhagoriaJL.Numerical investigation of flow through anartificially roughened solarairheater.IntJAmbientEnergy2014 http://dx.doi.org/10.1080/01430750.2013.823107.
[14] Yadav A S, Bhagoria J L, "A CFD Based Heat Transfer andfluid flow analysis of a conventional solar air heater,"Journal ofEngineering Science and Management Education, vol. 6, no. 2,pp. 138–147, 2013.

(This work is licensed under a Creative Commons Attribution 4.0 International License.)