International Journal of Research in Engineering, Science and Management
Volume-3, Issue-6, June-2020
www.ijresm.com | ISSN (Online): 2581-5792

Thermal Performance Evaluation of a Double Pass Solar Air Heater

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***Abstract*: Solar air heater is based upon solar thermal technology in which the energy from the sun is absorbed through an absorbing medium and used to heat air. A Solar air heater provides the significant use of solar energy, which uses the absorber plate to absorb the solar irradiations, converting it to thermal energy at its surface, and transferring the thermal energy to the fluid flowing through the duct. The thermal efficiency of the flat plate double pass solar air heater is observed to be low, due to low convective heat transfer coefficient at the absorber plate. To increase this heat transfer coefficient and thermal performance evolution, the effective way to attach artificial roughness elements on the absorber plate of the double pass solar air heater. The main area of concern of the present study is to show the effect variation of inclined-shaped artificial roughness element on heat transfer coefficient and friction factor of a solar air heater with rectangular duct and artificial roughness elements attached to both sides of the absorber plate.**

***Keywords*: Absorber plate, Inclined-shaped artificial roughness elements, Convective heat transfer coefficient, Solar air heaters, Thermal efficiency.**

1. Introduction

One of the most prominent applications of solar energy is the delivery of hot air for drying of textile, marine and agricultural products, heating of buildings for comfort conditioning, especially in the winter season. Various modifications and design optimization were presented by different authors. Numerous solar air heaters of different types also have been designed considering thermal performance and different application requirements.

[1] The solar air heater is a renewable energy heating device which is used to convert the solar energy into heat energy. Initially, the solar energy is collected over an absorber plate which is used to warm the air passing over it. In production plants, it is widely used. Space heating, wood seasoning, food dehydration, and drying of crops are some major applications of it.

[2] A viscous laminar sub boundary layer is presented near the adjacent to the absorber plate, due to this laminar sub boundary layer all the incident heat does not reach to the absorber plate, which is the main cause of low thermal efficiency and poor performance of solar air heater. For improving the thermal performance this laminar sub boundary layer should be destroyed. The turbulent flow over heat transfer surface area results in high convective heat transfer, so the turbulence must be created near the adjacent to absorber plate where the heat exchange takes place between absorber plate and flowing air and that can be achieved by using a roughened heating surface through the air side. The use of artificial roughness elements seems to be an attractive method for improving absorber plate thermal efficiency.

One of the well-known and frequently used methods so far for increasing the amount of heat transfer from the absorber plate is to use regular geometric roughness on the absorber plate through which air flow. This increase in the heat transfer between the absorber plate and fluid flowing produces turbulence in the path of flowing fluid, which further increases friction in the duct. For that purpose, proper geometry with improve rate of heat transfer with less friction penalty must be selected.

2. Literature Review

Energy is an essential requirement for human life. These energy resources can be broadly classified into non-conventional and conventional energy resources. The conventional energy resources are soon to deplete in the near future. Hence, the quest for mankind is to find renewable energy resources.

[3] Investigated the effect of the V-shaped roughness element attached to the absorber plate on both sides of the double-pass solar air heater having a rectangular duct on heat transfer and friction factor. It was reported that at relative roughness pitch of 10, an inclination angle of 600and relative roughness height of 0.033 heat transfer and friction factor are maximum.

[4] Satunanathan and Deonarine developed the idea of a double pass counter-flow air heater. They found double pass solar air heaters are 10-15% more effective than the single-pass solar air heater.

A. Reason for modification of simple solar air heater

The thermal efficiency of the double pass solar air heater having a smooth plate collector is reported to be very low due to the low convective heat transfer coefficient. The use of artificial roughness elements on both sides of the absorber plate is an effective way to enhance the heat transfer rate, at the expense of pressure drop. Various researchers have provided the artificial roughness element by fixing wires, ribs, wire mesh, or expanded metal mesh. In a smooth plate solar air heater, a thin viscous sub laminar boundary layer develops adjacent to the plate surface which causes the low relative velocity. In this region, the conductive heat transfer is dominated and beyond this convective heat transfer process is dominated. Thus our main focus is to improve this convective heat transfer process by increasing the convective heat transfer coefficient between the absorber plate and air flowing over the plate. Providing the roughness element not only increases the thermal efficiency but frictional losses also. Therefore, the blower required greater power. To keep these frictional losses to be low, the turbulence must be created only in the region very close to the duct surface i.e. in the sub laminar layer.

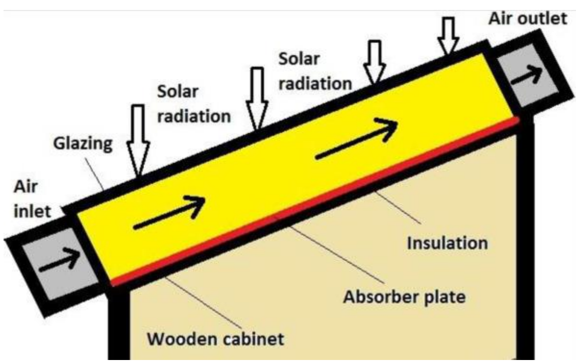

Fig. 1. Simple solar air heater

B. The method used for modification of solar air heater

By using the concept of 'Artificial Roughness'- Thermal performance of the double pass solar air heater can be improved by providing it on the absorber plate. The Smooth surface has a viscous and sub laminar layer because of that low heat transfer coefficient. To increase the heat transfer coefficient, turbulence has to be created adjacent to the surface of the plate. So, an artificial roughness technique is used for creating turbulences in a duct as shown in. To represent roughness following parameter are mostly used:

1. Relative pitch (P/e): It is a ratio of the distance between two consecutive ribs and the height of the rib.
2. Relative roughness height (e/Dh): It is the ratio of height of rib to the equivalent hydraulic diameter of the air passage.
3. The angle of attack (α): Inclination of a rib to with direction of flow in the duct.
4. The shape of roughness element: depend upon shape whereas it is 2-D, 3-D.
5. Aspect ratio: It is a ratio of width to the height of the duct (W/H).

C. Reasons for using roughness geometry used in experiment

The flow detaches as it joins the ribs and reaches about 6-7 rib height in a circular shape with rectangular ribs. The laminar layer is destroyed in the reattachment region. The boundary layer is reconstructed after the reattachment region, which is why its size is small. A recirculating region with frequent shading of vortices installed within the wake of ribs and is a vicinity of low warmth transfer coefficient. The turbulence along the wall in the process enhances the severity of heat transfer coefficient with a minimum pumping power penalty Compared to the smooth surface the presence of artificial hardness has been shown to increase the Nusselt count up to 3.24 times in the transitional to early turbulent flow design while the friction factor increases up to 5.3 instances through the researchers depending upon the relative roughness shape, and association of rib factors the thermal performance of roughened surface has been founded to increase.

3. Computer Aided Design (CAD) Model of Geometry and its Specifications

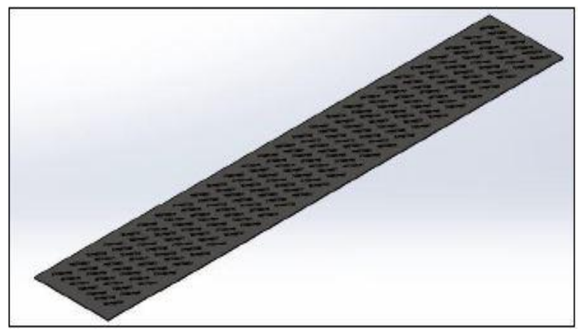

Fig. 2. CAD model of the absorber plate

Table 1
Absorber plate specifications

Plate Parameters	Value
Length(L)	1600 mm
Width(W)	250 mm
Thickness(T)	0.8 mm
Rib wire diameter(e)	3 mm
Pitch(P)	60 mm
Relative roughness pitch(P/e)	20
The angle of attack(α)	37^0(fixed)
Relative roughness height (e/Dh)	0.066(fixed)

In evaluation to many engineering design situations the inventor does no longer have business design ideas or product marketing specifications to guide the design effort Once a technical capability is set up inside the form of an invention the commercialization takes region through commercial layout and product attention research observed through layout for manufacturing The main advantage of this technique is the data conformity to the state of the art CAD structures which lets in trustworthy data transfer from CAD structures The consumer can nearly view the actual product on display make any modifications to it and present his/her thoughts on display with none prototype particularly at some point of the early ranges of the layout technique Cad structures can provide a digital prototype of the product on the early tiers of the layout manner which may be used for testing and evaluation Many human beings from various departments can percentage it they could explicit their opinion for the product at the early levels to complete the layout in less time and with the least mistakes.

Table 1, shows the specifications of the actual absorber plate which was used for the experiment.

4. Complete Experimental Setup

The schematic view of the experimental setup is shown in figure 2 and that of pictorial view in figure 4 respectively. The size of the rectangular duct (length×width×height) is (2070×250×25) mm. The entry length is 400mm, the length of the test section is 1600mm and space of 70mm is left at the end for the movement of air upside down.

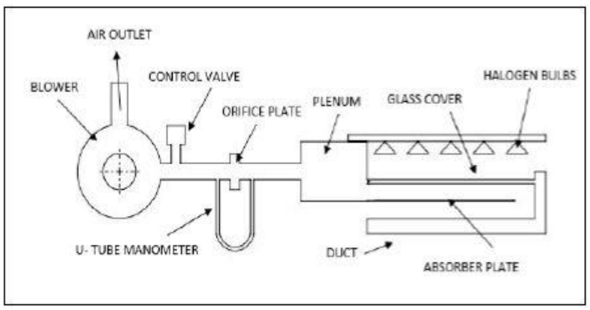

Fig. 3. Sketch of double pass solar air heater

Fig. 4. Actual experiment setup and Absorber plate setup

Table 2
Experimental setup specifications

Experiment parameter	Specification
Size of the entire duct	2070 mm×250mm×25mm
Length of the test section	1600 mm
Entry length	400 mm
Intensity of light (5halogen light of 500Weach)	900W/m^2
Glass sheet thickness	4 mm
Galvanized iron sheet for absorbing plate thickness	0.8 mm
Aluminum wire ribs attached to the upper and lower side of the absorber plate with resin and hardener	3 mm in diameter
Suction air blower of three-phase	3HP, 230 V and 3000rpm
Thermistor to measure the air and absorber plate at a different location	10k-ohm NTC
Pyrometer	Measure the intensity of light
Two gate valves	Precise control of air flow

The flow system consists of an entry section, test section, and an exit section, a flow measuring orifice plate, and a centrifugal blower with a control valve. The air enters at entry section and test section where the atmospheric air gets heated by taking heat from the absorber plate. Before starting the experimental all the thermocouples were checked carefully so that they give the room temperature and all the pressure tapings were checked for the leakage problem. A digital multimeter is used to indicate the output of the thermocouples through the selector switch.

5. Experimental Procedure

Before starting the experiment all the joints of the pipe, inlet and outlet section of the duct should be check for leakage. The experimental starts under a quasi-steady state to collect the relevant data for heat transfer and friction factor. The roughened absorber plate, having the desired roughness had been set and five values of flow rates were used for test runs. When the setup attains a steady-state process, then at different mass flow rates the following data was recorded to calculate heat transfer and friction factor. The steps included are as follows:

1. The temperature of air at the entry and outlet section of duct.
2. The temperature at twelve different locations on the absorber plate using thermistors.
3. The mass flow rate of air using orifice meter.
4. The pressure drop across orifice meter using a manometer.

6. Calculation and Data Reduction

The experimental data which is collected under a steady condition such as the temperature at different locations of the plate, pressure drops across test section and orifice, inlet and outlet air temperature at different mass flow rates were used to calculate the heat transfer, Nusselt number and friction factor. Relevant expressions for the computation of above-mentioned parameters and some intermediate parameters have been given below:

The mean plate temperature T_p is calculated by the average of the temperatures recorded at various locations on the absorber plate as,

$$T_p = \frac{T_3 + T_4 + T_5 + T_6 + T_7 + T_8 + T_9 + T_{10} + T_{11} + T_{12} + T_{13} + T_{14}}{12}$$

The bulk mean air temperature T_f is the arithmetic mean of the measured values of air temperature at the entry and exit to the test section calculated as

$$T_f = \frac{T_1 + T_2}{2}$$

The mass flow rate of air has been determined by the pressure drop measured across the calibrated orifice meter using the following expression

$$m = C_d A_0 \sqrt{\frac{2\rho(\Delta P_0)}{1 - \beta^4}}$$

The velocity of air is calculated from the knowledge of mass flow rate and area of flow, i.e. the cross-section area of the duct as,

$$V = \frac{m}{\rho W H}$$

The hydraulic diameter of the rectangular section of the duct is determined from the relationship as given below,

$$D_h = \frac{4A_c}{P}$$

The Reynolds number of airflow in the duct is calculated from the following relationship

$$R_e = \frac{\rho V D_h}{\mu}$$

Pressure drop *(ΔP_{duct})* measured across the test section length is used to find out the friction factor using Darcy Wiesbach equation as below,

$$f = \frac{2(\Delta P_{duct})D_h}{4\rho L V^2}$$

The heat transfer coefficient h is calculated from the relationship given below,

$$h = \frac{Q_h}{A_p(T_p - T_f)}$$

Where Tp and Tf are the mean absorber plate and the fluid temperatures, respectively, as discussed above and heat transfer rate (Qu) to the air is given by

$$Q_u = mC_p(T_0 - T_i)$$

The heat transfer coefficient calculated using above equation is used to determine the Nusselt number as given below

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

The experimental setup is validated by comparing the Nusselt number and friction factor value for a smooth plate calculated from experimental data with actual value defined from the Dittus-Boelter equation and modified Blasius equation respectively. The equations used are formulated below

Dittus-Boelter equation: N_{us}=2×.024×$Re^{0.8}$×$Pr^{0.4}$

Modified Blasius equation: f_s=2×0.085×$Re^{-0.25}$

7. Experimental Data

Table 3
Experimental readings for smooth plate

Manometric Head (m)	Air Inlet temperature T_i	Air outlet temperature T_0	Absorber Plate temperature T_P
0.04	27.45	34.84	41.92
0.03	27.68	35.32	43.27
0.02	27.34	35.98	44.21

Table 4
Experimental readings for rough plate

Manometric Head (m)	Air Inlet temperature Ti	Air outlet temperature T_0	Absorber Plate temperature T_P
0.04	27.62	36.28	42.81
0.03	27.44	36.86	43.54
0.02	27.73	37.54	46.34

The above observed readings are then used for the deduction of the various parameters which were defined before using the various known formulae and then the results of those parameters are calculated using MATLAB.

A. Calculated data after the experiment

Table 5
MATLAB calculated parameters for smooth plate

Parameter	Reading 1	Reading 2	Reading 3
Air temperature (^{0}C)	31.145	31.5	31.66
Mass flow rate (kg/sec)	0.03487	0.030184	0.024639
Velocity (m/s)	4.871417	4.221232	3.447527
Reynolds Number	13890.19	12008.7	9799.821
Heat gain (Watt)	259.3104	232.0366	214.2001
Heat transfer coefficient (W/m^2K)	60.16482	49.2856	42.66934
Nusselt Number	105.4004	86.23563	74.63697
Friction factor	0.01597	0.016884	0.01753
Thermal efficiency (%)	72.0306	64.45461	59.5000

Table 6
MATLAB calculated parameters for rough plate

Parameter	Reading 1	Reading 2	Reading 3
Air temperature (^{0}C)	31.95	32.15	32.365
Mass flow rate (kg/sec)	0.034827	0.030151	0.024599
Velocity (m/s)	4.8778	4.2257	3.45303
Reynolds Number	13871.84	11995.905	9784.17
Heat gain (Watt)	303.472	285.792	242.818
Heat transfer coefficient ($W/m^2.K$)	69.860	62.7288	44.2937
Nusselt Number	122.3852	109.7574	77.4783
Friction factor	0.01655	0.01753	0.01899
Thermal efficiency (%)	84.2979	79.3868	67.4494

8. Experimental Results Evaluation and Validation

A. Effect on Nusselt number with Reynolds number

From fig. 5 it has been observed that Nusselt number increases more gradually with the increase of Reynolds number for the given value of relative roughness pitch (p/e) as compared to the smooth duct. This is due to a distinct change in the fluid flow characteristics as a result of roughness that causes flow separations, reattachments and the generations of secondary flows.

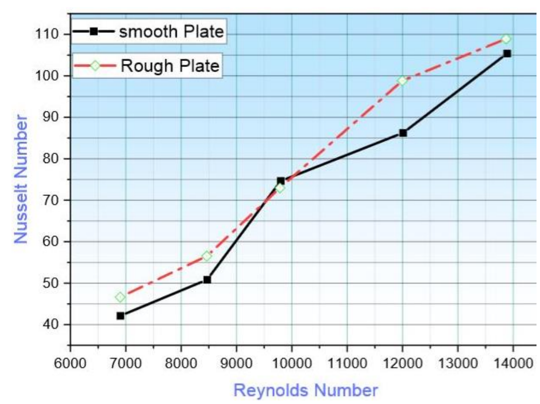

Fig. 5. Comparison of actual Nusselt number for smooth plate and rough plate

B. Effect on friction factor with Reynolds number

The friction factor is affected by the Reynolds number. The variation of friction factor with Reynolds number for a smooth plate is shown in fig. 6. It can be seen that the friction factor decreases with an increase of the Reynolds number.

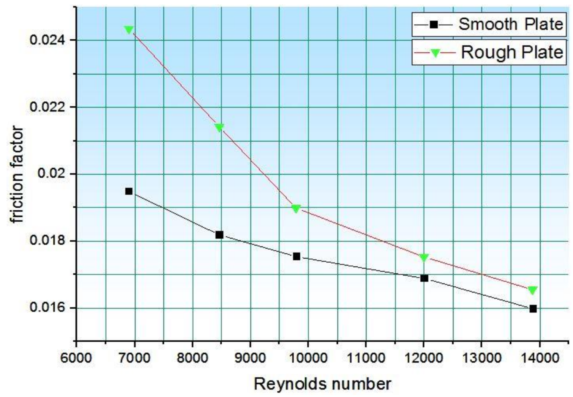

Fig. 6. Comparison of friction factor of a smooth plate with that of rough plate

C. *Effect on thermal efficiency with Reynolds number*

The efficiency of the solar air heater is the main approach of this study is to enhance the heat transfer coefficient and efficiency of the double pass solar air heater. From this figure, it has been observed that the efficiency of the artificially roughened plate increases more rapidly than that of a smooth absorber plate by 10-15%. The maximum experimental thermal efficiency of double pass solar air heater has been found to be 84.3% at the relative roughness pitch of 20.

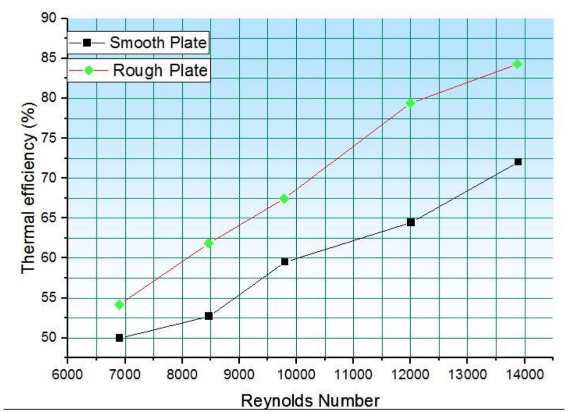

Fig. 7. Comparison of thermal efficiency of a smooth plate with that of a rough plate

9. Conclusion and Results

The following conclusions are drawn from this work:

1. Generally, Nusselt number increases with an increase of the Reynolds number it has been concluded from figure 5 that the values of the Nusselt number are considerably higher for the rough plate in comparison to the smooth plate This change occurs because of the change in fluid flow properties as a result of the roughness that causes separation of fluid flow reattachment and generation of secondary flow.
2. The maximum increment of the Nusselt number is found for an angle of attack 37^0, while providing the artificial roughness to the smooth duct. The optimum value of the angle of attack is obtained due to the flow separation and the secondary flow, which was the result of providing inclined ribs and the movement of resulting vortices.
3. It is found that the Nusselt number increases with an increase of Reynolds number. The variation of Nusselt number with relative roughness pitch (p/e) is insignificant at lower values of Reynolds number, but at higher Reynolds number there is a substantial effect.
4. The maximum experimental thermal efficiency obtained from double pass solar air heater is 84% at relative roughness pitch of 20 while it was around 70% in case of a smooth plate under the same environment
5. The friction factor also varies with the Reynold number.
6. Nusselt number increases and friction factor decreases with increases of Reynolds number. Roughness causes flow separation, reattachment and generation of secondary flow, so performance higher as compare to a smooth absorber plate.
7. By providing the artificial roughness, the thermal performance of the absorber plate increases with the minimum friction factor. All those techniques used to improve the thermal performance of a solar air heater have better results 2 to 4 times that of a smooth surface.

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