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Effect on Thermal Boundary Layer, by Roughened Surface of Solar Air Heater Duct

Dilip Gehlot
M. Tech. Scholar, Thermal Engineering, LNCT, Indore, Madhya Pradesh, India
Ashok Kumar Gupta
Assistant Professor and HOD, Mechanical Engineering Department
Rishiraj Institue of Technology, Indore, MP, India
Prakash Gawali
Assistant Professor, Mechanical Engineering Department, LNCT, Indore, Madhya Pradesh, India
Dr. A. C. Tiwari
Professor & HOD, Mechanical Engineering Department, UIT, RGPV, Bhopal, MP, India

Abstract:
As is well known that, the thermo-hydraulic boundary layer formation is dependent on the surface geometry and flow of fluid through the plates used for the flow. Therefore, an experimental investigation has been carried out to study the effect on thermo-hydraulic boundary layer by using 2W (4V) type of artificial roughness geometry of the absorber plate of solar air heater. The experiments were performed to collect the data for the forced convection flow of air in solar air heater rectangular duct; with one broad wall roughened by 2W shaped ribs. The evaluation of Reynolds number has been carried out for this artificial roughness geometry, in the absorber plate of solar air heater duct. The range of parameter used in this experiment has been decided on the basis of practical consideration of the system and operating conditions. The Result has been compared with smooth duct under similar flow and boundary conditions. It is found from the investigation that on increasing the roughness of a roughened plate the Reynolds number also increases, thus increasing the turbulence of the flow.

***Key words**: Boundary Layer, Reynolds Number, Turbulence, Solar Air Heater, Roughened Surface*

1. Introduction

Life is but a continuous process of energy conversion and transformation. The accomplishments of civilizations have largely been achieved through the increasingly efficient and extensive harnessing of various forms of energy to extend human capabilities and ingenuity. Energy is similarly indispensable for continued human development and economic growth. Providing adequate, affordable energy is essential for eradicating poverty, improving human welfare, and raising living standards worldwide.

Basically, energy is the key input in economic growth, there is a close link between the availability of energy and the future growth of a nation. The standard of living of the people of any country is considered to be proportional to the energy consumption by the people of that country. In one sense, the disparity one feels from country to country arises from the extent of accessible energy for the citizens of each country. The word ‘energy’ is derived from the Greek word ‘en-ergon’ which means ‘in-work’ or ‘work-content’. So, ‘energy’ can simply be defined as “the capacity to do work” and is an indirectly observed physical quantity. There are various sources of energy available for mankind to harness. Of all the sources, solar energy is the earliest form of energy known to mankind, but perhaps the least utilized by it. Solar energy is globally distributed and free from depletion or embargo and present no environmental problems. Solar energy is very large, inexhaustible source of energy. The power from the sun intercepted by the earth is approximately 178 billion MW, which is about 10,000 times larger than the present energy demand. Thus, in principal, solar energy could supply all the present and future energy needs of the world on a continuing basis. This makes it one of the most promising of the unconventional energy sources. Although it is abundant, solar energy impinging on the earth’s atmosphere is relatively dilute (approx.1352 W/m^2). Transverse the earth’s atmosphere dilute is further by attenuation, local weather phenomena and air pollution. Moreover, solar energy is received only intermittently at any point on earth. Areas lying between 30^0N to 30^0 S latitudes receive maximum solar radiations. Thus, India (8^0 N to 32^0 N) is blessed with abundant solar radiation. On an average India’s annual solar energy potential is about 7000 MJ/m^2.

In order to make solar energy usable economical, one of the important requirements is its efficient collection. Solar collectors are used for that purpose. A solar collector is a special type of heat exchangers that converts insulation (heat flux) into thermal energy. These are generally of two types-

- Flat plate type solar collector.
- Concentrating (focusing) type solar collector.

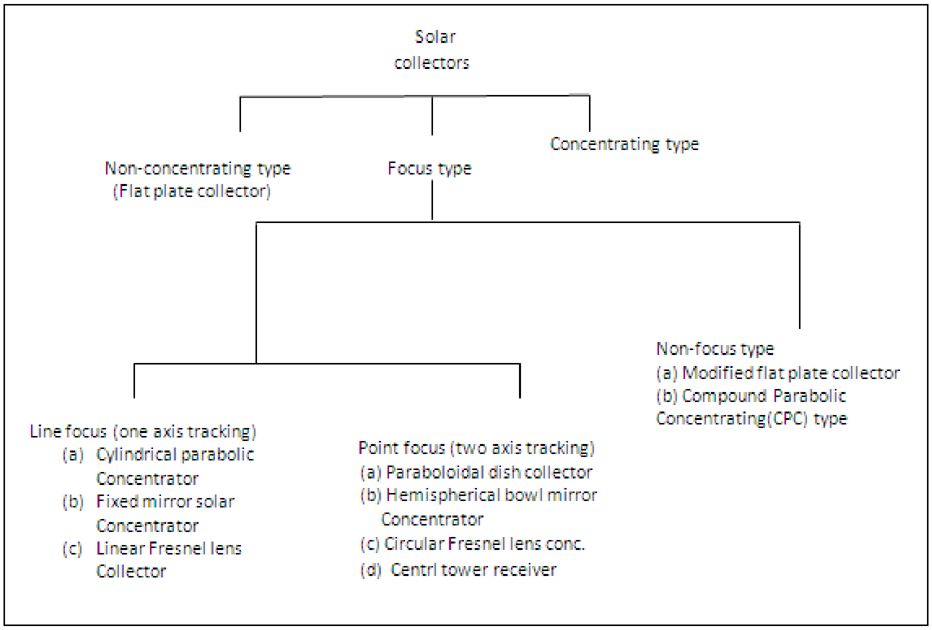

Figure 1: Shows Different Types of Solar Collectors

A solar air heater is a device used to produce hot air for any industrial level drying application by using the freely available sun, without using conventional fuels like electricity, diesel, LPG, firewood, coal, etc., but it could be coupled with an existing conventional drying systems like Tray dryers, tunnel Driers, Conveyor Drier, FBD drier and bin drier operated by conventional fuels to save fuel consumption. A conventional solar air heater consists of an absorber plate and parallel plate below, forming a passage of high aspect ratio, through which the air to be heated flows. Like a liquid flat plate collector, a solar air heater is simple in design (Fig. 2) and requires little maintenance. In addition, since the fluid does not freeze, the solar air heater has the advantage of not requiring any special attention at temperatures below 0^{o}C. Corrosion and leakage problems are also less severe.

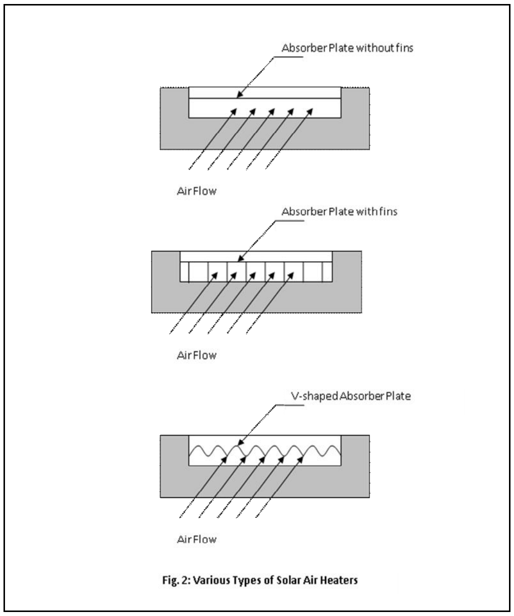

Figure 2: Shows the Different Types of Solar Air Heaters

However, the value of the heat transfer coefficient between the absorber plate and air is low and these results in roughened or longitudinal fins to be provided in the flow passage.A roughness element is used to improve the heat transfer coefficient by creating turbulence in the flow. However, it would also result in increased friction losses and hence the greater power requirement for pumping air through the duct. In order to keep the friction losses at a low level, the turbulence must be created only in a region very close to duct surface, i.e. in laminar sub layers. A further disadvantage associated with the use of solar air heater is that large volume of fluid has to be handled. As a result, the pressure becomes an important parameter and has to be kept in prescribed limits.

2. Effect of Artificial Roughness on Turbulence & Friction Factor

It is well known that in a turbulent flow a laminar/viscous sub-layer exists in addition to the turbulent core. The artificial roughness on heat transfer surface breaks up the laminar boundary layer of turbulent flow and makes the flow turbulent adjacent to the wall. The artificial roughness that results in the desirable increase of heat transfer also result in an undesirable increase in the pressure drop due to the increased friction: thus the design of the flow duct and the absorber surface of solar air heaters should, therefore, be executed with the objectives of high heat transfer rates and low friction losses. To balance useful energy and friction losses, second considerations are suitable, and exergy is a suitable quantity for the optimization of solar air heaters having different design and roughness elements. The artificial roughness on the absorber surface may be created, either by roughening the surface randomly with a sand grain/sand blasting or by use of regular geometric roughness. A roughness type can be described by the dimensionless geometrical parameters namely the relative roughness height (e/D; The ratio of roughness height to the hydraulic diameter of the passage), the relative roughness pitch (P/e: the ratio of the distance of two successive roughness elements to the height of the roughness), the angle of attack (α: the angle of the roughness rib with respect to the direction of flow) and the shape of the roughness elements (square, rectangular or circular etc.). For a specific roughness type a family of geometrically similar roughness is possible e.g. by changing relative roughness height and maintaining other geometrical parameters to be the same [1], [2], [3], [4] and [5].

3. Experimental Set-Up

The Experimental schematic Diagram set-up including the test section is shown in the fig. 3. The flow system consists of an entry section, a Test Section, an Exit section, a flow meter and a Centrifugal Blower. The duct is of the size 2043 mm x 200mm x 25mm (dimension of the inner cross section) and it is constructed from wooden panel of 25mm thickness.

In the exit section of 200 mm three equally spaced baffles are provided in a 100 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.

An electric heater having a size of 1650mm X 150mm was fabricated by combining series and parallel loops of heating wire on 5mm asbestos sheet. Mica sheet of 1mm is placed between the electric heater and absorber plate. This mica sheet acts as an insulator between the electric heater and absorber plate (G.I. Sheet). The heat flux may vary from 0 to 1000 W/m^2 across it. The back of the heater is covered by a 50 mm glass wool layer and a 12 mm thick plate of wood to insulate the top of the heater assembly.

The side of the entire set-up, from the inlet to the orifice plate is insulated with 25mm thick polystyrene foam having a thermal conductivity of 0.037 W/m-k. The heated plate is a 1mm thick G.I. Sheet with integral rib-roughness formed on its rear side and this form the top broad wall of the duct, while the bottom wall is formed by 25 mm wood with insulation below it.

The mass flow rate of the air is measured by means of a calibrated orifice meter connected with an inclined manometer, and the flow is controlled by the control valve provided in the lines. The orifice plate has been designed for the flow measurement in the pipe of inner Diameter of 53mm, as per the recommendation of [6]. The orifice plate is fitted between the flanges so aligned that it remains concentric with the pipe. In the present experiment set-up, we used 830 mm pipe length on the up-stream and 2060 mm on down-stream side. The calibrated copper constantan 0.3 mm (24 SWG) Thermocouple were used to measure the air and heated plate Temperature at different locations. The location of thermocouple wire on the heated wall is shown in fig. 4. A Digital voltmeter is used to indicate the output of the thermocouple wire. The temperature measurement system is calibrated to yield temperature value ±1 ^{o}C. The pressure drop across the test section was measured by a micro manometer.

It is an open loop that consists of a test Duct with entrance and exit sections a blower, a control Valve, Orifice plate and various devices for measurement of temperature and fluid flow. The flow system consists of an entry section, a test section, an exit section a flow meter and a blower. The test set-up consists of a wooden duct of size 2043 mm X 200 mm X 25mm (Dimensions of inner cross section) and is constructed of wooden block of 25 mm thickness.The test section is of length 1500 mm (33.75 D_h). The entry and exit length were 177 mm ($2.5\sqrt{WH}$) and 353 mm ($5\sqrt{WH}$) respectively.

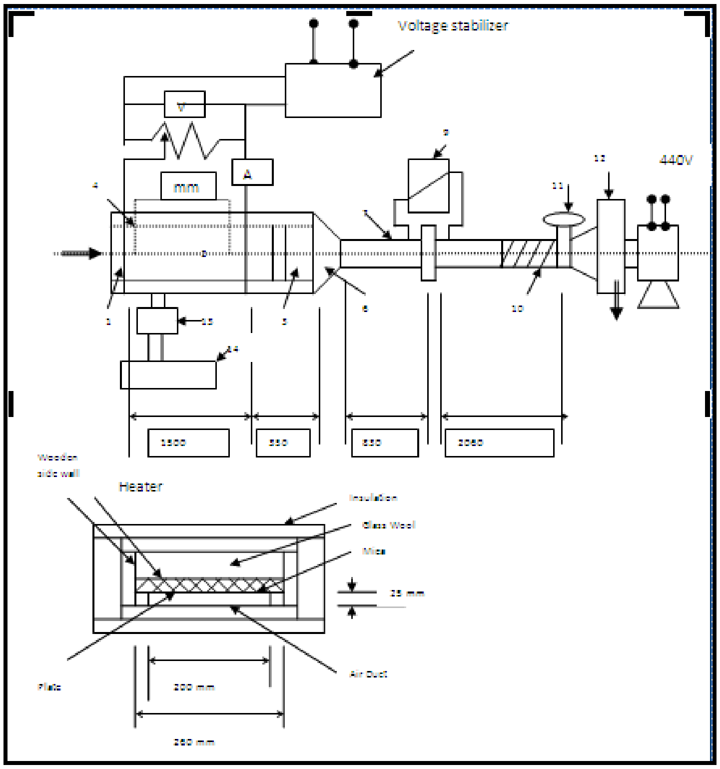

Figure 3: Experimental set up

Here,

1 entrance length192 mm
2 Test section 1360 mm
3 Exit Section 350mm
4 Absolute Plates 1500X200
5 Duct lower side
6 Transition section
7 G.I. Pipe Outer Dia. 65 mm
8 Orifice Plate
9 Inclind Mano meter
10 Flexible Pipe 210 mm
11 Control Valve, 12 Blowers 3 HP, 13 Selector Switch&14 Temperature Recorder
A Ammeter, V Volt Meter, T_i Inlet Air Temperature&T_o Outlet Air Temperature

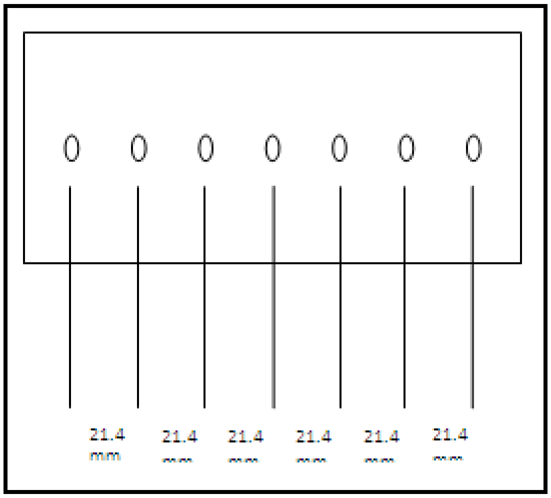

Figure 4: Shows the Location of Thermocouples

4. Results and Discussion

As mentioned, experimental data have been collected for smooth plate (fig. 5(a)) and 2W type roughened plate (fig. 5(b)). Many runs have been taken with different mass flow rates. The experimental data have been used to determine the Reynolds Number (Re) and hence, compare the results.

Figure 5(a): Smooth Plate

Figure 5(b): 2W Roughened Plate

4.1. Data Reduction

Equations used in the calculation are:

4.2. Mean Air & Plate Temperature

The mean air temperature or average flow temperature T_{fav} is the simple arithmetic mean of measure values at the inlet and exit of the test section. Thus,

$$T_{fav} = (T_i + T_o)/2$$

Parameter	**values**
Reynolds number	: 3000-12000
Aspect Ratio	: 8.0
Test Length	: 1500 mm
Hydraulic Diameter, D	: 44.44 mm
Relative height, e	: 1.3 mm
Relative roughness Height (e/D)	: 0.0292
Relative Roughness Pitch	: 10 mm
Solar insolation (I)	: 750 W/m^2
Plate material	: G.I.Sheet
Thickness of Plate	: 1 mm
Angle of attack, α	: 60^o

The mean plate temperature, T is the weighted average of readings, of nine locations on the absorber plate.

4.3. Pressure Drop Calculation

Pressure drop measurement across the orifice plate was calculated by following equation,

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

Where, ΔP_o = Pressure difference,

ρ_m = Density of fluid,
Δh = Difference of liquid head in U-tube manometer.

4.4. Mass Flow Measurement

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

$$m = c_d x A_o x \ [2\rho\Delta P/(1 - \beta^4)]^{0.5}$$

Where, m = mass flow rate, Kg/s
c_d = Coefficient of discharge of orifice i.e. 0.62
A_o = Area of orifice plate, m^2
ρ= Density of air i.e. 1.1576 Kg/m^3
β = ratio of dia. (d_o/d_p) i.e. 26.5/53=0.5

4.5. Velocity Measurement

$$V = m / \rho WH$$

Where, m= mass flow rate, Kg/s
ρ= Density of air i.e. 1.1415 Kg/m^3
H= height of the duct, m (0.025)
W= width of duct, m (0.2).

4.6. Reynolds Number

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

$$Re = VD / \upsilon,$$

Where, kinematic viscosity, υ = 15.48 x 10-6 m2/sec, and
Hydraulic dia., D= 4WH / 2(W+H)

Insolation (I),W/m^2	**Inlet Temp.(T_i) ^{o}C**	**Outlet Temp.(T_o) ^{o}C**	**Average Plate Temp. (T_p)**	**Average Flow Temp. (T_{fav})**	**Reynolds Number (Re)**
720	36.490	48.001	77.000	42.250	3685
720	36.491	46.003	73.000	41.250	5013
720	35.324	44.002	65.000	40.000	7115
720	35.324	42.491	63.000	38.910	9425
720	34.101	40.010	59.500	37.055	12418
720	34.002	38.490	54.000	36.250	14926

Table 1: Observation Table for Smooth Plate

Insolation (I),W/m^2	**Inlet Temp.(T_i) ^{o}C**	**Outlet Temp.(T_o) ^{o}C**	**Average Plate Temp. (T_p)**	**Average Flow Temp. (T_{fm})**	**Reynolds Number (Re)**
720	37.269	59.002	78.580	48.130	3636
720	38.001	57.003	76.002	47.502	4794
720	39.002	55.500	73.507	47.249	6796
720	34.110	52.000	71.500	43.055	9780
720	34.110	47.002	61.501	40.548	12144
720	34.110	44.003	56.008	39.055	14348

Table 2: Observation Table for (2W Shaped) Roughened Plate

5. Conclusion

The present work was undertaken with the objective of extensive investigation into 2W shaped rib as artificial Roughness on the underside of one broad wall of solar air heater. Results have been compared with those of a smooth duct under similar flow conditions to determine the effect on Reynolds Number and hence, turbulence of the Thermo-hydraulic Boundary Layer.

The following conclusions have been drawn from this investigation:

- In the entire range of Reynolds number, it is found that the turbulence increases for Roughened plate.
- On roughing the plate, the turbulence and hence, heat transfer increases.

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