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REVIEW ARTICLE

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A REVIEW ON THE INVESTIGATION OF SOLAR AIR HEATER WITH SPIRAL COIL VERTICAL ROUGHENED ABSORBER PLATE

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ABSTRACT

The heat is transferred between air and the absorber plate in a solar air heater. In general, the thermal performance of a solar air heater is low because of poor heat transfer between the absorber plate and air. It can probably be improved by enhancement of heat transfer from the absorber plate by the use of artificial roughness. This technique is gaining importance among the researchers since long time and a lot of research is still going on and has further scope. Artificial roughness in the form of spiral coil on the absorber plate is another technique to enhance the rate of heat transfer to flowing fluid in the roughened duct of solar air heater. Mathematical modelling and factors affecting collector performance have also been discussed. Moreover result and conclusion have been discussed from the graphs of Nusselt vs Reynold's no, & friction factor and Reynolds no.

Nomenclatures:

T_a-ambient temperature, T_p-plate temperature, T_{in} -inlet temperature, T_f -average air temperature T_g -glass temperature, U_t -top heat loss coefficient, U_b -back heat loss coefficient, H_c -convection heat coefficient, $H_{rp\text{-}g}$ -radiation heat loss coefficient from plate to glass, $H_{rp\text{-}s}$-radiation heat loss coefficient from plate to sky, H_w -wind convection heat loss confident, I-solar radiation, a absorptivity of absorber plate, m-Mass flow rate of air, t-transmittivity of the glass cover.

1. INTRODUCTION

Energy is required to sustain our life. The energy resources available on the earth in various forms like sunlight, fossil fuels, hydraulic energy, wind energy, tidal energy, geothermal energy and nuclear energy resources etc. energy resources may be classified in two ways i.e. conventional and non-conventional energy resources. Our demand of energy is increasing continuously and rapidly with increase in the population of world. Conventional energy sources like coal and petroleum are rapidly depleting. Saving of energy for future as well as finding alternative energy resources to fulfil our demands in future should be our aim. Solar energy is the best source of energy to fulfil our present and future demands. Sun is the ultimate source of energy. It is easily available anywhere, abundant quantity in nature, available free of cost and its use is free from pollution in nature. It is inextinguishable resources of energy that provides clean energy. Solar energy is available on the earth in the form of solar radiation. This radiation needs to be harnessed for making proper use of sunlight. Various types of solar collectors are used to convert solar energy into heat and further it can be transformed into the other form of energy.

2. HEAT TRANSFER ENHANCEMENT TECHNIQUES:

Heat transfer inside flow passages can be enhanced by using passive surface modifications such as rib tabulators, protrusions, pin-fins and dimples. These heat transfer enhancement techniques have practical application for internal cooling of turbine air coils, combustion chamber liners, and electronics cooling devices, bio medical devices and heat exchangers. The heat transfer can be increased by these following different augmentation techniques. They are broadly classified into three different categories-

- Passive techniques.
- Active techniques.
- Compound techniques

3. CONCEPT OF ARTIFICIAL ROUGHNESS

Artificial roughness is basically a transfer enhancement technique by which thermo hydraulic performance of a solar air heater can be improved. The thermal efficiency of solar air heater is generally poor due to low heat transfer co-efficient between the absorber plate and the air flowing in to the duct due to the formation of laminar sub layer on the absorber plate which acts as heat transferring surface. So there is a need to break the laminar sub layer therefore, artificial roughness has been used extensively for the enhancement of forced convective heat transfer, which further requires flow at the heat-transferring surface to be turbulent. However, energy for creating such turbulence has to come from the fan or blower and the excessive power is required to flow air through the duct. Therefore, it is desirable that the turbulence must be created only in the region very close to the heat transferring surface, so that the power requirement may be reduced.

This can be done by keeping the height of the roughness element to be small in comparison to duct dimension. The basic dimensionless geometrical parameters that are used to characterize roughness are:

1. Relative roughness pitch (p/e): Relative roughness pitch (p/e) is defined as the ratio of distance between two consecutive ribs and height of the rib.
2. Relative roughness height (e/D): Relative roughness height (e/D) is the ratio of rib height to equivalent diameter of the air passage.
3. Angle of attack (α): Angle of attack is inclination of rib with direction of air flow in duct.
4. Aspect ratio: It is ratio of duct width to duct height. This factor also plays a very crucial role in investigating thermo-hydraulic performance.

3.1 Shape of Roughness Elements Instead of relative roughness pitch, relative roughness height and angle of attack, shapes of various roughness elements also influence the heat transfer coefficient and friction factor. Different shapes of roughness elements are discussed as below: -

3.1.1 *V- shaped rib*

Momin,Saini,Solanki [1] investigated the effect of geometrical parameters of V-shaped ribs on heat transfer and fluid flow characteristics of rectangular duct of solar air heater with absorber plate having V-shaped ribs on its underside have been reported. The range of parameters for this study has been decided on the basis of practical considerations of the system and operating conditions. The investigation has covered a Reynolds number (Re) range of 2500–18000, relative roughness height (e=D/h) of 0.02–0.034 and angle of attack of flow (α) of 30˚–90˚for a fixed relative pitch of 10. It was found that Rate of increase of Nusselt number with an increase in Reynolds number is lower than the rate of increase of friction factor. The maximum enhancement of Nusselt number and friction factor as a result of providing artificial roughness has been found to be respectively 2.30 and 2.83 times that of smooth duct for an angle of attack of60˚. The thermo-hydraulic performance parameter improves with increasing the angle of attack of flow and relative roughness height and the maxima occurs with an angle of attack of 60˚. It was found that for relative roughness height of0.034 and for angle of attack of 60˚, the V-shaped ribs enhance the values of Nusselt number by 1.14 and 2.30 times over inclined ribs and smooth plate case at Reynolds number of 17034. It means that the V-shaped ribs have definite advantage over the inclined ribs for similar operating conditions.

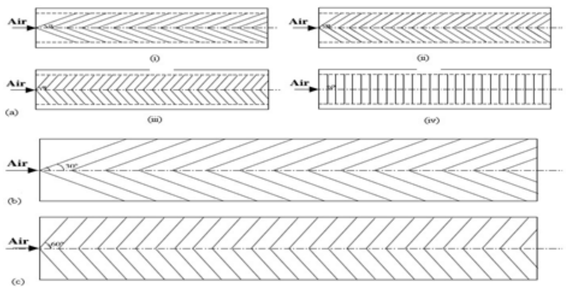

Fig. 1 (a) Roughness elements on absorber plate. (b) Schematic diagram of 30˚Vshaped ribs

3.1.2 *Integral chamfered ribs*

Karwa,Solanki,Saini[2] investigated the performance of solar air heaters with chamfered repeated rib-roughness on the airflow side of the absorber plates have been reported. The roughened elements have a relative roughness pitch of 4.58 and 7.09 while the rib chamfer angle is fixed at 15°. For the airflow duct depths of 21.8, 21.5 and 16 mm, the relative roughness heights for the three roughened plates used are0.0197, 0.0256 and 0.0441, respectively. The airflow rate per unit area of absorber plate has been varied between 0.024 to 0.102 kgs21 m22 (flow Reynolds number ranges from 3750 to 16350.

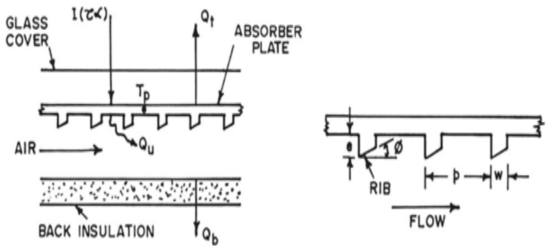

Fig. 2 (a) Solar Air heater with roughened absorber plate (b) Integral chamfered rib

The study shows substantial enhancement in thermal efficiency (10 to 40%) over solar air heaters with smooth absorber plates due to the enhancement in the Nusselt number (50% to 120%). The thermal efficiency enhancement is also accompanied by a considerable enhancement in the pumping power requirement due to the increase in the friction factor (80% to 290%). The artificial roughness on the absorber plate also causes 1.8 to 3.9 times increase in the friction factor. The enhancements in the Nusselt number, friction factor and thermal efficiency are found to be strong functions of the relative roughness height. The greatest enhancement is observed for the air heater with the highest relative roughness height.

3.1.3 *Wedge shaped ribs*

Bhagoria,Saini,Solanki[3] performed this experiment to collect heat transfer and friction data for forced convection flow of air in solar air heater rectangular duct with one broad wall roughened by wedge shaped transverse integral ribs. The experiment encompassed the Reynolds number range from 3000 to 18000; relative roughness height 0.015 to 0.033; the relative roughness pitch 60.17Φ-1.0264<p/e<12.12; and rib wedge angle (f) of 8, 10, 12 and 15°. The effect of parameters on the heat transfer coefficient and friction factor are compared with the result of smooth duct under similar flow conditions. They reported that as compared to the smooth duct, the presence of ribs yields Nusselt number up to 2.4 times while the friction factor rises up to 5.3 times for the range of parameters investigated. The maximum heat transfer occurred for a relative roughness pitch of about 7.57,while the friction factor keeps decreasing as the relative roughness pitch increases and a maximum enhancement of heat transfer occurs at a wedge angle of about 10°while on either side of this wedge angle, Nusselt number decreases. The friction factor increased as the wedge angle increases.

3.1.4. *Broken transverse ribs*

Sahu and Bhagoria[4] carried out this experimental investigation to study the heat transfer coefficient by using 90˚ broken transverse 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 10–30 mm, height of the rib of 1.5 mm and duct aspect ratio of 8. The air flow rate corresponds to Reynolds number between 3000–12,000. The heat transfer results have been compared with those for smooth ducts under similar flow and thermal boundary condition to determine the thermal efficiency of solar air heater.

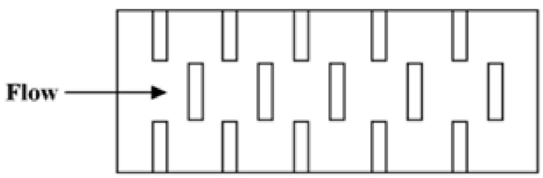

Fig.3 Broken transverse rib

In this investigation it is found that the Nusselt number increases, attains a maximum for roughness pitch of 20 mm and decreases with an increase of roughness pitch. The value of the Nusselt number increases sharply at low Reynolds number and this becomes constant or increases very slightly in comparison to low Reynolds number. The maximum enhancement of heat transfer coefficient occured at pitch of about 20 mm. It was also concluded that at low Reynolds number (below 5000) a smooth duct gives better heat transfer than the artificial roughened duct. The experimental values of the thermal efficiency of the three roughened absorber plates tested have been compared with the smooth plates. A plate having roughness pitch 20 mm gives the highest efficiency of 83.5%.

3.1.5. *Rib- grooved roughness*

This investigation carried out by Jaruker,Saini,Gandhi[5] encompassed the Reynolds number range from 3000 to 21,000; relative roughness height 0.0181–0.0363; relative roughness pitch 4.5–10.0, and groove position to pitch ratio 0.3–0.7. This investigation clearly demonstrates that the heat transfer coefficient for rib-grooved arrangement is higher than that for the transverse ribs, whereas the friction factor is slightly higher for rib-grooved arrangement.

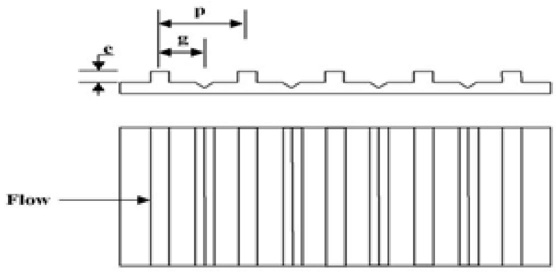

Fig.4 Rib grooved roughness

In this experiment it was concluded that as compared to the smooth duct, the presence of rib grooved artificial roughness yields Nusselt number up to 2.7 times while the friction factor rises up to 3.6 times. The maximum heat transfer occurs for a relative roughness pitch of about 6.0, and it decreases either side of relative roughness pitch and similar trend is observed for friction factor. The optimum condition for heat transfer occurs at a groove position to pitch ratio of 0.4, while on the either side of this ratio, both Nusselt number and friction factor decreases. It is found that the rib-grooved arrangement provides the best thermo-hydraulic Performance and hence can be employed for heat transfer augmentation.

3.1.6. *Combination of inclined and transverse rib*

Varun,Saini,Singal[6] carried out this experiment to study the heat transfer and friction characteristics by using a combination of inclined as well as transverse ribs on the absorber plate of a solar air heater. The experimental investigation encompassed the Reynolds number (Re) ranges from 2000 to 14 000, relative roughness pitch (p/e) 3–8 and relative roughness height(e/Dh)0.030.

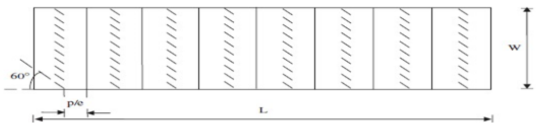

Fig. 5 showing combination of inclines and transverse rib.

Results have been compared with those of a smooth duct under similar flow conditions to determine heat transfer coefficient and friction factor. The thermal performance of roughened solar air heater is influenced by the roughness parameters and the best performance has been found for the roughness parameter that yield maximum heat transfer coefficient. The geometry having relative roughness pitch of 8 have the maximum thermal efficiency.

3.1.7. Gap in inclined continuous rib

Aharwal,Saini,Gandhi[7] done this experiment to to present the experimental investigation of heat transfer and friction factor characteristics of a rectangular duct roughened with repeated square cross-section split-rib with a gap, on one broad wall arranged at an inclination with respect to the flow direction. The duct has a width to height ratio (W/H) of 5.84, relative roughness pitch (P/e) of 10, relative roughness height (e/Dh) of 0.0377, and angle of attack (α) of 60˚. The gap width (g/e) and gap position (d/W) were varied in the range of 0.5–2 and 0.1667–0.667, respectively. The heat transfer and friction characteristics of this roughened duct have been compared with those of the smooth duct under similar flow condition. The effect of gap position and gap width has been investigated for the range of flow Reynolds numbers from 3000 to 18,000.

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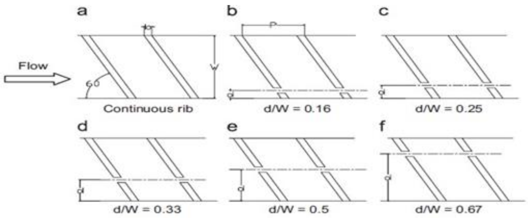

Fig 6. showing inclines continuous rib roughness

In this investigation it was found that a gap in the inclined rib arrangement enhances the heat transfer and friction factor of the roughened ducts. The increase in Nusselt number and friction factor is in the range of 1.48–2.59 times and 2.26–2.9 times of the smooth duct, respectively, for the range of Reynolds numbers from 3000 to 18,000. The maximum values of Nusselt number and friction factor are observed for a gap in the inclined repeated ribs with a relative gap position of 0.25 and a relative gap width of 1.0.

3.1.8. Metal rib grit roughness

Karmare and Tikekar[8] investigated about thermo hydraulic performance of roughened solar air heaters with metal rib grits. The range of variation of system and operating parameters was investigated within the limits of, e/Dh: 0.035–0.044, p/e: 15–17.5 and l/s as 1.72, against variation of Reynolds number, Re: 3600–17000. The study shows substantial enhancement in thermal efficiency (10–35%), over solar air heater with smooth collector plate.

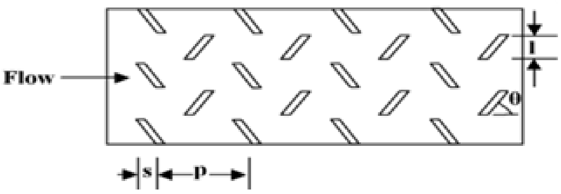

Fig.7 Metal grit ribs

It was discovered that Nusselt number and friction factor increases up to 2 and 3 times respectively when compared to smooth surface. Heat transfer had its maximum value at e/D=0.044, l/s = 1.72, p/e = 17.5 and friction factor had its maximum value at e/D = 0.044, l/s = 1.72, p/e = 12.5. Optimum performance was found for e/D = 0.044, l/s = 1.72, p/e = 17.5. The thermal efficiency enhancement was also accompanied by a considerable increase in the pumping power requirement due to the increase in the friction factor (80–250%).

3.1.9. Transverse chamfered rib groove

Layek,Saini and Solanki[9] carried out this experiment on heat and fluid flow characteristics of fully developed turbulent flow in a rectangular duct having repeated integral transverse chamfered rib-groove roughness on one broad wall. The roughened wall is uniformly heated while the remaining three walls are insulated. These boundary conditions correspond closely to those found in solar air heaters. Six roughened plates has been tested placing a 60˚ V-groove at the centre line in between two consecutive chamfered ribs. The ribs' top have been chamfered having chamfer angles of 5˚,12˚,15˚, 18˚, 22˚and 30˚,while relative roughness pitch (P/e) and relative roughness height (e/Dh) of the ribs were kept constant having values of 10 and 0.03 respectively. The flow Reynolds number of the duct varied in the range of approximately 3000–21,000, most suitable for solar air heater. They reported that as compared to smooth surface the roughened surface can yield a maximum of about 2.6-fold and 3.35-fold increase in the Nusselt number and friction factor respectively in the range of parameters investigated.

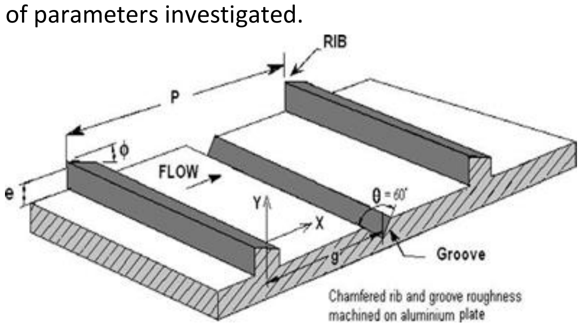

Fig. 8 showing artificial roughness

The maximum enhancement of Nusselt number occurs for chamfer angle of 18°but the friction factor increases monotonously with increase in chamfer angle. A substantial improvement in the thermo-hydraulic performance was obtained, as indicated by the performance parameter value lying between 1.4 and 1.76 for the range of experimentation.

3.1.10. Arc shaped roughness

Solanki and Saini[10] carried out this experimental study for enhancement of heat transfer coefficient of a solar air heater having roughened air duct provided with artificial roughness in the form of arc-shape parallel wire as roughness element. Increment in friction factor by provided with such artificial roughness elements has also been studied. The effect of system parameters such as relative roughness height (e/d)0.0215-0.0422,(p/e)10 and arc angle (α/90)0.3333-0.6666 have been studied on Nusselt number (Nu) and friction factor (f) with Reynolds number (Re) varied from 2000 to 17000. .

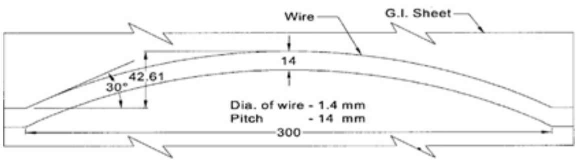

Fig.9 showing arc shaped roughness

It was concluded that considerable enhancement in heat transfer coefficient is achieved by providing arc-shape parallel wire geometry as artificial roughness with solar air duct. The maximum enhancement in Nusselt number has been obtained as 3.80 times corresponding the relative arc angle (a/90) of 0.3333 at relative roughness height of 0.0422. However, the increment in friction factor corresponding to these parameters has been observed 1.75 times only.

3.1.11. 60°inclined continuous discrete rib

SanjayKumar,VijayMittal,N.S.Thakur,Anoop Gautum [11] carried out this experimental study for enhancement of heat transfer coefficient of a solar air heater having roughened air duct provided with artificial roughness in the form 60°inclined discrete rib. Increment in friction factor by provided with such artificial roughness element has also been studied. The effect of system parameters such as relative roughness height (e/D) 0.0249,0.0374 &0.0498, relative roughness pitch (P/e)8,12&16 and relative gap position (d/W) 0.15,0.25&0.35 have been studied on Nusselt number (Nu) and friction factor (f) with relative gap width (g/e) 1 and Reynolds number (Re) varied from 4105 to20526.

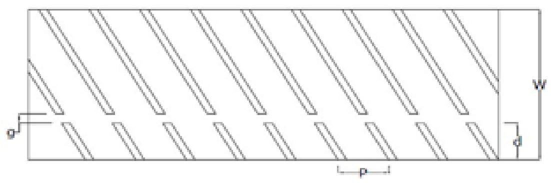

Fig.10 Geometry of 60° inclined discrete rib roughness

Based on experimental result it was concluded that as compared to smooth surface the roughened surface can yield a maximum of about 2.75 fold 3.72 fold increase in nusselt number and friction factor respectively in the range of parameter investigated. The maximum heat transfer enhancement occurs for relative roughness pitch of 12, relative gap position of 0.35and relative roughness height of 0.0498.

3.1.12. Continuous M shaped ribs turbulators.

Sachin Chaudhary,Varun,Manish Kumar Chauhan[12] concern this experiment with enhancement of heat transfer coefficient using artificial roughened absorber plate on solar air heater. In this study M shape geometry has been studied which is having different orientation. The effect of roughness parameters relative roughness height (e/D), relative roughness (P/e) and angle of attack (α) on Nusselt number and friction factor have been seen. The range of Reynolds number 3000-22000, e/D, P/e and α are 0.037-0.0776, 12.5-75 and 30-60° respectively.

After carrying out the detailed experimental investigation, it was studied that the heat transfer and friction factor characteristics of solar air heater duct which is having M shape artificial roughness on absorber plate. It was reported that Nusselt number is increasing monotonously with the increase in Reynolds number. On the other hand, friction factor also increased which leads to higher pumping power. It is necessary to obtained optimum parameters for artificial roughness M shape geometry. It has been observed that maximum heat transfer occurred at 0.07769 (e/D), 25 (P/e) and 60° while maximum friction factor occurs at 0.07769 (e/D), 25 (P/e) and 45°. A maximum heat transfer enhancement due to presence of artificial roughness has been found about 1.7-1.8 times as compared to smooth plate. Lanjewar, Bhagoria and Sarviya[13] carried out this experiment to study heat transfer, friction characteristics and thermo hydraulic performance of roughened absorber plate in solar air heater by using W-shape rib roughness, the roughened wall being heated while the remaining three walls insulated. The roughened wall has relative roughness height (e/Dh) 0.018, relative roughness pitch (p/e) 10, rib height 0.8 mm, angle of attack in the range of 30º-60º and duct aspect ratio (W/H) 8. The air flow rate corresponds to Reynolds number between 2300 - 14000.

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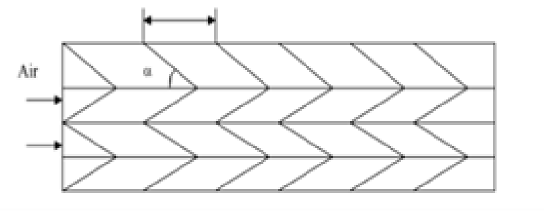

Fig. 11 W-shaped roughness geometry

It was reported that the enhancement in Nusselt number over the smooth duct was 32-92%, 31-81% and 9-56% for 60º, 45º and 30º respectively. Friction factor ratios for these arrangements were 1.39-1.57, 1.32-1.43 and 1.17-1.27 respectively. Thermohydraulic performance parameter improved with increasing the angle of attack of flow and best performance occurs with an angle of attack of 60º. Friction factor results were compared with the correlation for a smooth rectangular duct given by modified blasius equation $f_s = 0.085\ Re^{-0.25}$.

4. Solar Air Heater

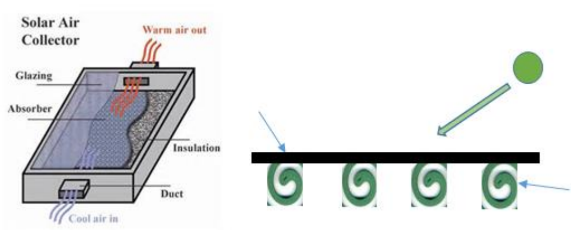

Fig.12 Representation of vertical spherical coil roughened absorber plate

Major components are: 1) Transparent cove. 2) Blackened absorber plate. 3) Ducts.4) Weather tight insulated container.

solar air heaters have been made in variety of designs. In some the absorber surface beneath the glazing, includes overlapped, spaced, clear and black glass plates, single smooth metal sheets, flow through stacked screen or mesh, corrugated metal plates, finned metal sheets and others. In other air passing beneath the plate or underlying air passage reduces downward heat loss and one or two covers of glass or transparent plastic provide resistance to upward convection and radiation losses. There are various types of solar air heater which are used for enhancement of thermal performance:

a) Honeycomb collector
b) Double exposure collector
c) Thermal trap collector
d) Two pass collector
e) Double flow type collector
f) Overlapped glass plate collector
g) Artificial roughened absorber plate

A CFD investigation of artificial roughened isosecels right triangle worked by Rajeev Ranjan et al.[20] found that Solar air heater with isosceles right triangle gives 3.06 times enhancement in Nusselt number in comparison to that of a smooth plate. The maximum average Nusselt number is 70 for relative roughness pitch 3.33and relative roughness height 0.045.Maximum thermo-hydraulic performance is obtained for relative roughness pitch of 5 and relative roughness height 0.03.

4. **MATHEMATICAL MODELING:**

The collector under consideration consists of a glass cover and absorber plate with a well-insulated parallel bottom plate, forming a rectangular duct profile through which the air to be heated flows. The corrugation of the absorber plate is trapezoidal in shape and the air is made to flow along the corrugation. The theoretical solutions of the thermal performance of the SAH system involve the formulation of the energy balance equations that describe the heat transfer mechanisms at each component of the solar air collector. The heat distribution through the air heater is as shown in Fig 3 below. The energy balance equations obtained are as follows:

On the glass cover:

$H_{rp\text{-}g}(T_p - T_g) + h_c(T_g - T_f) = U_t(T_g - T_a)$ --- (1)

On the absorber plate:

$(\tau\alpha)AI = Ah_c(T_p - T_f) + Ah_{r,p\text{-}g}(T_p - T_g) + AU_b(T_p - T_a)$ --- (2)

The air flow: $\dot{m}C_p(T_{out} - T_{in}) = Ah_c(T_g - T_f) + Ah_c(T_p - T_f)$ --- (3)

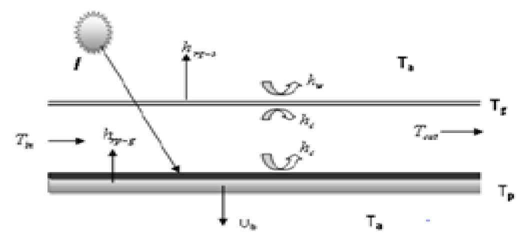

Fig. 13 The heat distribution through the air heater

The equations (1) to (3) are used to derive the solutions for the collector components‟ temperatures, i.e. Tp, Tg and Tout as follows:

$T_p = \frac{(\tau\alpha)AI + h_{rpg}T_g + h_cT_f + U_bT_a}{h_{rpg} + h_c + U_b}$ --- (4)

$T_g = \frac{h_{rpg}T_p + h_cT_f + U_tT_a}{h_{rpg} + h_c + U_t}$ --- (5)

$T_{out} = \frac{A_p h_c}{mC_p}[T_p+T_g-2T_f] + T_{in}$ --- (6)

It is assumed that there is linear temperature rise in the channel, hence Tf is evaluated as the mean of the inlet and the outlet temperatures:

$Tf = \frac{T(out)-T(in)}{2}$ --- (7)

By using these temperatures, we find out the total useful heat absorbed by the vertical spiral absorber plate

Qu=Ac[I(τα)]-QL --- (8)

Where QL = AcUL(Tp – Ta)

QL = total heat losses

UL = heat transfer coefficient corresponding to losses

Thus calculating the Instantaneous Efficiency $(\eta_i) = \frac{q}{IA}$

Where qu = Qu, Now, if a blower is attached to the solar air heater then

Friction factor (f) is given by Blasius equation f = 0.079 Re-0.25

Pressure Drop is then calculated using- Pressure drop = $\frac{4f\rho L_1 v^2}{2D_h}$

Discharge from duct is given by (Area of Duct) x (Fluid Velocity)

Mechanical Power (M.P) required to pump the air from the Heater = (Discharge from duct) x (Pressure Drop)

6. RESULT & DISCUSSION

An investigation of the performance of solar air heaters with different artificially roughened surface on the airflow side of the absorber plates has been carried out.

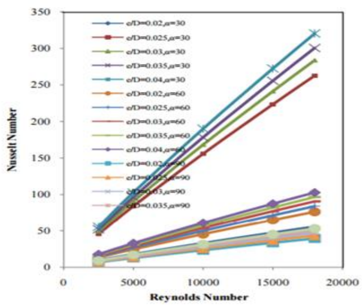

Fig 14. Showing the variation of Nusselt Number with the Reynolds number at different set of operating parameters.

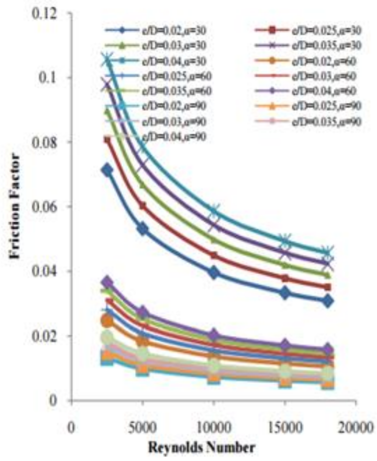

Fig 15. Showing the variation of Friction Factor with the Reynolds number at different set of operating parameters.

It is found from fig 14 & 15 that rate of increase of Nusselt number was observed to be lower than the rate of increase of friction factor with an increase in Reynold's number. The maximum enhancement of Nusselt no and friction factor as a result of providing artificial roughness had been found to be 2.3 to 2.83 times respectively over smooth duct for an angle of attack of 60o. It was reported that for relative roughness height value of 0.034 & angle of attack of 60o gives the best results. It is also found that at angle of attack of 300 gives normally same results as that for smooth duct. Different graphs also show that the enhancement of Nusselt number is upto 120-150% for an angle of attack of 60o and upto 400-500% for the angle of attack of 30o for the higher values relative roughness height but this tends to higher increase in friction losses. Thus it is found to be compensatory at e/D of 0.034 & for attack of 60°.

7. CONCLUSION

In this paper the review of effect of artificial roughness by providing different shape geometry on solar absorber plate by different investigators has been studied along with the study of new artificial roughness called "spiral coil vertical roughness", which shows that artificial roughness enhances the heat transfer rate.

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