A Review on Optimization of Thermo-Hydraulic Performance of Solar Air Heater by Implementing Artificial Roughness

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***Abstract*— In solar heater and heat exchanger their performance characteristic can be effectively improved by implementing artificial roughness in different forms such as ribs, wire mesh, dimple shape roughness ,baffles etc. Basically on implementing artificial roughness, surface area within heater or heat exchanger increases, this result in higher value of heat transfer. To resolve the effect of these geometries on thermal performance of solar heater sand heat exchangers, several experimental and numerical studies have been conducted out by various researchers and reveal the effect of shape factor in thermal performance of solar heater and heat exchanger. In this paper extensive review has been carried out over various roughness element geometries which are employed in air heaters and heat exchangers in expressions of heat transfer, friction factor and flow simulation techniques. Moreover, various correlations between heat transfer and friction factor for different roughness geometries are also discussed.**

Keywords- Roughness, Heat Transfer, Friction Factor and Solar air heater

I. INTRODUCTION

In the current period, when there is an incessant demand of energy for the economic development and industrialization, sustainable as well as renewable energy sources are playing crucial role in this regard, in order to design for the high performance heat transfer systems. Heat transfer augmentation in these thermal systems has several applications for day to day including heating of agriculture products, space heating or cooling, in electronics systems and others various industries. For many substitutions, in India solar energy has high solar remoteness. It is clean, natural and available in sufficient amount. It is devices which are designed for the use of solar energy and it works on the principle of conversion of solar energy into thermal energy. They are considered as the most cost effective out of all other designed products, which is based on solar energy mainly for the commercial and industrial applications. Schematic illustration of the solar air heater is shown in Fig. 1. Solar air heaters are the devices which absorb the incoming solar radiations and convert it into thermal energy at the absorbing surface.

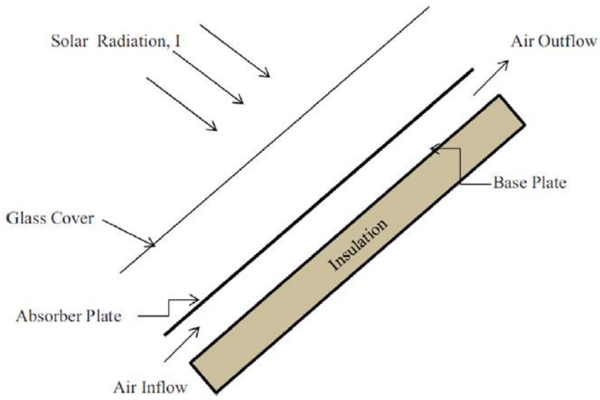

Fig.1.Schematic Diagram Of Conventional Solar Heater.

The thermal efficiency of solar air heaters has been found to be generally poor because of low convective heat transfer coefficient between the absorber plate and air flowing in the duct. This is because of the formation of laminar viscous sub-layer which resists the heat transfer. The attempts adopted to augment the heat transfer includes provision of artificial roughness on the under-side of absorber plate in the form of ribs, grooves, dimples, winglets, baffles, twisted tapes, mesh wires, etc. Artificial roughness is a passive heat transfer enhancement technique by which thermo hydraulic performance of a solar heater can be improved. As the air flows through the duct of a solar air heater, a laminar sub layer is formed over the observer surface that obstruct heat transfer to the flowing air, thereby adversely affecting the thermal performance of the solar air heater. In order to attain higher heat transfer coefficient, it is enviable that flow at the heat transferring surface is made turbulent. However energy for creating such turbulence has to come from fan, which in turn increases the power requirement. So artificially roughened absorber plate is considered to be a good methodology to increase the heat transfer coefficient since it break laminar sub layer in order to reduce thermal resistance. But this also causes simultaneous increase in friction loss in duct. It is therefore desirable to create turbulence in the region very close to the heat transfer-ring surface i.e. in the laminar sub layer only, in order to reduce the friction loss with the application of artificial roughness and power requirement may be lessened. This can be done by keeping the height of the roughness elements to be small in comparison with the duct dimension.).

II. THERMAL PERFORMANCE OF SOLAR AIR HEATER

Hottel–Whillier–Bliss equation reported by Duffie and Beckman [1] is commonly used to calculate thermal performance of solar air heater. It is given as

$$Q_u = A_s F_R [I(\tau\alpha)_e - U_L (T_i - T_a)]$$

Through duct the energy gain from flowing air can be evaluate by using,

the following equation:

$$Q_u = m C_p F_R (T_0 - T_i) = h A_s (T_{pm} - T_{fm})$$

As discussed above, heat transfer coefficient (h) is represented in non-dimensional form by using relationship of Nusselt number (Nu) reported by Duffie and Beckman [1].

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

III. INVESTIGATIONS OF ARTIfiCIALLY ROUGHENED SOLAR AIR HEATER FOR PERFORMANCE ENHANCEMENT

The thermal efficiency of solar air heaters is found to be low due to low heat transfer coefficient on the air side. Heat transfer coefficient has been significantly enhanced by providing artificial roughness on absorber plate surface exposed to air which may be created, either by roughening the surface randomly with a sand grain/sand blasting or by use of regular geometric roughness. As in solar air heater the solar radiation is absorbed by absorber plate, which is the main heat transfer surface; therefore, the solar air heaters are modeled as a rectangular duct having one rough wall and three smooth walls. Different geometries of roughness elements on the under-side of absorber plate studied by various investigators.

(a) Transverse wire rib roughness

The use of small diameter wire attached on the under-side of absorber plate as a artificial roughness was first presented by Prasad and Mullick [2] to improve the thermal performance of solar air heater for drying purposes. The experimental study was conducted using the parameters 0.019 as relative roughness height (e/D_h) and 12.7 as relative roughness pitch (p/e). It is investigated that protruding wires improve plate efficiency factor from 0.63 to 0.72 resulting in 14% improvement in thermal performance. Prasad and Saini [2,7,16] investigated the effect of protrusions from underside of absorber surface in the form of small diameter wires on heat transfer and friction factor for fully developed turbulent flow in a solar heater duct. Experimental investigation was carried out for the relative roughness pitch (p/e) of 10, 15, 20 and relative roughness height (e/D_h) of 0.020, 0.027 and 0.033 to detect the effect of height and pitch of roughness on heat transfer and friction factor. The maximum value of Nusselt number and friction factor is reported 2.38 and 4.25 respectively for the pitch of 10. The roughness geometry used is shown in Fig.2

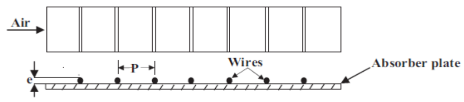

Fig.2. Transverse Wire Rib Roughness [2,7,16]

For Heat transfer,

$$S_t = (f/2)/[1+\sqrt{f/2\{4.5(e^+)^{0.28}}\,\mathrm{Pr}^{0.57} - 0.95(P/e)^{0.53}\}]$$

Friction factor,

$$f = 2/[0.95(P/e)^{0.53} + 2.5\ln(D/2e) - 3.75$$

b) 90° broken transverse rib roughness

Sahu and Bhagoria [9] investigated effect of 90° broken transverse ribs on heat and fluid flow characteristics using rough-ness height of 1.5 mm, duct aspect ratio value of 8, pitch in the range of 10–30 mm and Reynolds number in the range of 3000–12,000. Heat transfer enhancement was reported to be 1.25–1.4 times over smooth duct. From the experiment maximum thermal efficiency was found in the order of 83.5%. Geometry used has been shown in Fig.3

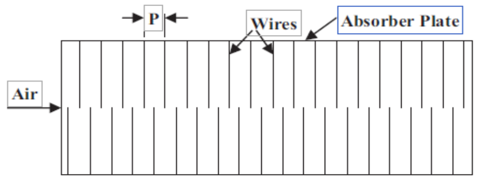

FIG.3. 90° BROKEN TRANSVERSE RIB ROUGHNESS [9]

c) Inclined continuous rib roughness

Investigators found out that inclined rib gives better heat transfer than transverse ribs due to generation of secondary flow which helps in breaking of the laminar sub layer. Han and Park [4] studied experimentally the effect of inclined ribs in narrow aspect ratio ducts which results in heat transfer enhancement. The effect of relative roughness height (e/d), inclination of rib with respect to flow direction and Reynolds number (Re) on the thermo hydraulic performance of a roughened solar air heater for transitionally rough flow region (5oeþ o70) is studied by Gupta et al. [6]. The experimental result shows that maximum heat transfer and friction factor was in the order of 1.8 and 2.7 times respectively, corresponding to values of angle of inclination as 601 and 701, respectively. At a relative roughness (e/D) value of 0.023 and Reynolds number value of 14,000, a comparatively best thermo hydraulic performance was reported by investigator. The roughness geometry investigated has been shown in Fig. 4

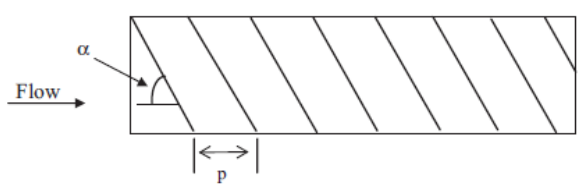

Fig.4. Inclined Continuous Rib Roughness [4,6]

For Heat transfer,

$$Nu = 0.000824(e/D)^{-0.718}(W/H)^{0.284} \quad \text{for } e \leq 35$$
$$\bullet \mathrm{Re}^{0.284} \exp[-0.04(1-\alpha/60)^2](k/D)$$

For Friction factor,

$$f = 0.06412(e/D)^{0.019}(W/H)^{0.237}$$
$$\bullet \mathrm{Re}^{-0.185} \exp[-0.0993(1-\alpha/60)^2]$$

(d) Inclined continuous rib roughness with gap

Aharwal et al. [11] studied the effect of width and position of gap in inclined split-ribs having square cross section on heat transfer and friction characteristics of a rectangular air heater duct. The increase in Nusselt number and friction factor was 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. Corresponding to a relative gap width (g/e) value of 1.0 and relative gap position (d/W) value of 0.25, values of heat transfer, friction factor ratio (f/fs) and thermo hydraulic perfor-mance parameters were found to be maximum. It was investigated that relative gap width beyond 1.0 reduces the flow velocities through the gap and which reduces heat transfer as compared to continuous ribs. If the relative gap width was taken lower than 1.0, then it shrinks the passage for secondary flow release which reduces the turbulence intensity behind the gap and hence reduces heat transfer. The geometry investigated has been shown in Fig.5

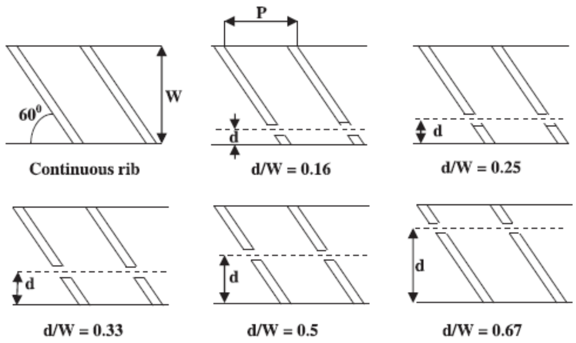

Fig.5. Inclined Continuous Rib Roughness With Gap [11, 12]

(e) V-shaped rib roughness

Hans et al. [13] carried out an experimental investigation to study the effect of multiple v-rib roughness on heat transfer coefficient and friction factor in an artificially roughened solar air heater duct as shown in Fig.6. The experiment encompassed Reynolds number (Re) from 2000 to 20,000, relative roughness height (e/D) values of 0.019–0.043, relative roughness pitch (P/e) range of 6–12, angle of attack (α) range of 30–75° and relative roughness width (W/w) range of 1–10. Correlations for Nusselt number and friction factor in terms of roughness geometry and flow parameters were developed. A maximum enhancement of Nusselt number and friction factor due to presence of such an artificial roughness was found to be 6 and 5 times, respectively, in comparison to the smooth duct for the range of parameters considered. The maximum heat transfer enhancement was found to occur for a relative roughness width (W/w) value of 6 while friction factor attains maximum value for relative rough-ness width (W/w) value of 10. It was also found that Nusselt number and friction factor attain maxima corresponding to angle of attack (α) value of 60°. Maximum enhancement of Nusselt number and friction factor was observed corresponding to relative roughness pitch (P/e) value of 8 while Nusselt number and friction factor increased monotonically with increase in the value of relative roughness height (e/D). The geometry investigated has been shown in Fig.6

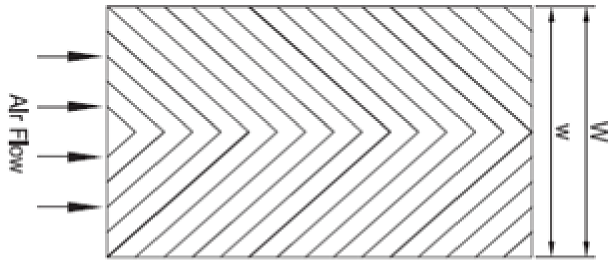

Fig.6. V-Shaped Rib Roughness [13]

For Heat transfer,

$$Nu = 3.35\times10^{-5}\,\mathrm{Re}^{0.92}(e/D)^{0.77}(W/w)^{0.43}(\alpha/90)^{-0.49}$$
$$\cdot\exp[-0.1177(\ln(W/w))^2]\exp[-0.061(\ln(\alpha/90))^2]$$
$$(p/e)^{8.54}\exp[-2.0407(\ln(p/e))^2]$$

For Friction Factor,

$$f = 4.47\times10^{-4}\,\mathrm{Re}^{-0.3188}(e/D)^{0.73}(W/w)^{0.22}(\alpha/90)^{-0.39}$$
$$\exp[-0.52(\ln(\alpha/90))^2](p/e)^{8.9}\exp[-2.133(\ln(p/e))^2]$$

(f) Arc shaped rib roughness

Saini and Saini [10] experimentally studied the effect of arc shaped ribs on heat transfer and fluid flow characteristics of rectangular duct of solar air heater as shown in Fig7. This experimental investigation covered a Reynolds number range of 2000–17,000, relative roughness height (e/D) of 0.0213–0.0422 and relative angle of attack of flow (α/90) of 0.3333–0.6666 for a fixed relative roughness pitch (P/e) of10. Fig. 7 shows schematic diagram of experimental set-up for this investigation. The maximum enhancement in Nusselt number was obtained as 3.80 times corresponding to the relative arc angle (α/90) of 0.3333 at relative roughness height of 0.0422. However, the increment in friction factor corresponding to these parameters was observed 1.75 times only. Based on the experimental values, correlations for Nusselt number and friction factor were developed. The geometry investigated has been shown in Fig.7

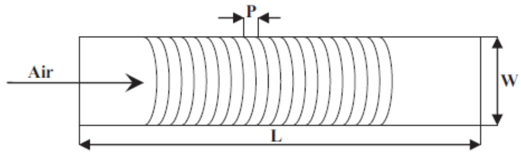

Fig.7. Arc Shaped Rib Roughness [10]

For Heat transfer,

$$Nu = 0.001047(e/D)^{0.3772}(\alpha/90)^{-0.1198}\,\mathrm{Re}^{1.3186}$$

For Friction Factor,

$$f = 0.14408(e/D)^{0.1765}(\alpha/90)^{0.1185}\,\mathrm{Re}^{-0.17103}$$

It is essential to determine the geometry that will results in the maximum enhancement in heat transfer and minimum increase in friction factor. This is done using a factor developed by Lewis known as efficiency parameter, η which evaluates the enhancement of heat transfer for same pumping power requirement. It is defined as

$$\eta = (Nu_r / Nu_s) / (f_r / f_s)^{0.333}$$

Correlations of heat transfer and friction factor for different roughness geometries are used to derive thermo hydraulic performance. Comparisons are made for the geometries having relative roughness pitch (P/e) value as 10 and relative roughness height (e/D_h) value as 0.04. Range of Reynolds number is taken in between 2000 - 20,000. Thermo hydraulic performance parameter comparison of different types of ribs has been shown in Fig.8

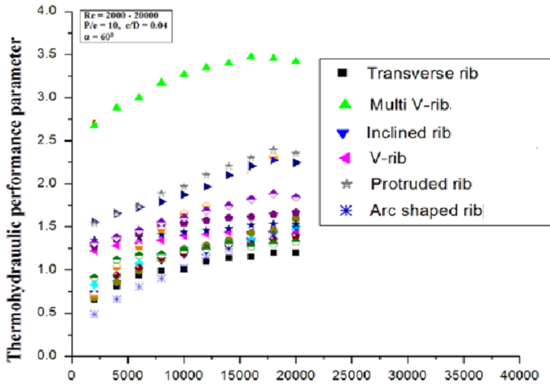

Fig.8 Comparison Of Enhancement Factor Of Different Geometries

IV. Conclusion

1) The use of artificial roughness on a surface of Solar air heater is an effective technique to enhance heat transfer to fluid flowing in the duct. Artificially roughened solar air heaters have enhanced rate of heat transfer as compared to the smooth solar air heaters under the same geometric/operating conditions.
2) It has been found that roughness geometries being used in solar air heaters are of many types depending upon shapes, size, arrangement and orientations of roughness elements on the absorber plate.
3) There are several parameters that illustrate the roughness elements, but for solar air heater the most preferred roughness geometry is repeated rib type which is described by the dimensionless parameters viz. relative roughness height (e/Dh), relative roughness pitch, (P/e), angle of attack (α), channel aspect ratio (W/H) etc.
4) Transverse rib roughness enhances the heat transfer coefficient by flow separation and generation of vortices on the upstream and downstream of rib and reattachment of flow in the inter-rib spaces.
5) It can be recognized that the use of artificial roughness results in higher friction and hence higher pumping power requirements. It is desirable that design of solar air heater should be made in such a way that it should have transfer maximum heat energy to the flowing fluid with minimum consumption of blower energy.
6) Analytical correlations for calculating heat transfer and friction factor are derived for different roughness geometries are postulated.

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