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Various Roughness Geometries used in Solar Air Heater – A Review

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Abstract— Energy is the primary input required to sustain the growth of any nation. As today, the world's environment is facing a serious threat of depleting fossil fuels, thus in order to sustain the economic growth new technologies are required to be developed that can efficiently utilize energy generated from earth's natural resources. Utilization of solar energy to convert it into thermal energy by solar air heater is one of them. But, the thermal efficiency of a solar air heater is found to be significantly low. Thus, in order to enhance the efficiency of solar air heater, the technique of using artificial roughness on the heat transfer plate is considered as effective technique to enhance the thermal efficiency. The objective of this paper is to review various studies in which different artificial roughness are used to enhance the heat transfer rate and thermal efficiency of the solar air heater.

Keywords — Solar air heater, Artificial roughness, Heat transfer rate.

I. Introduction

Solar energy provides an inexhaustible, non-polluting source of energy and is available throughout the year. The most efficient way of utilization of solar energy is to convert it into thermal energy by using solar air heaters which absorb the incoming solar radiations on the absorber plate and convert it into thermal energy and transfer this energy to fluid flowing through the collector in the duct. The thermal efficiency of a conventional solar air heater is observed to be poor due to the formation of boundary layers on the heat transferring surface. The low heat transfer coefficient between the absorber and the flowing air is contributed due to low thermal conductivity and relatively low velocity of air. Provision of various turbulence promotes in the form of artificial roughness on the underside of the absorber plate is an effective technique to achieve the enhanced thermal efficiency of the solar air heaters.

Concept of Artificial Roughness: In convective heat transfer among all the available methods of enhancing the thermal efficiency, artificial roughness is consider to be an efficient method. In order to get higher values of heat transfer coefficient, the flow at the absorber plate has to made turbulent but this transfer surface i.e. laminar sub layer, also the height of roughness element should be kept small as compare to that of the duct dimensions. The shape of the roughness element over the absorber plate is defined by several parameters and among all of them roughness element height (e) and roughness element pitch (P) are the most important parameters. The artificial roughness is also defined by certain non-dimensional parameters. These parameters include Relative Roughness Pitch (P/e), Relative Roughness Height (e/D), Angle of Attack (α), Aspect Ratio and shape of the roughness element.

Effect of rib: The presence of rib produces the most important effect on the flow pattern by generating two flow separating reigns, one on each side of the rib. Thus the enhancement of heat transfer and friction losses occurs due to the turbulence created by the vortices generated by the presence of rib.

Effect of rib height and pitch: As the rib height and pitch are changed, pattern downstream of the rib as there is generation of flow separation downstream of the rib, thus for a pitch ratio of less than 8, reattachment of shear layer is not observed. The heat transfer is observed to be maximum near the reattachment point. It is also thought that decrease in relative roughness pitch (P/e) having a fixed relative roughness height (e/D), can produce a similar effect. The decrease in heat transfer will occur for relative pitch having value of 8 as there would be no reattachment. As well as relative roughness pitch having value beyond 10 would also lead to decrease in the enhancement of heat transfer. Thus, it is concluded that an optimum ambition of pitch and height would lead to maximum enhancement.

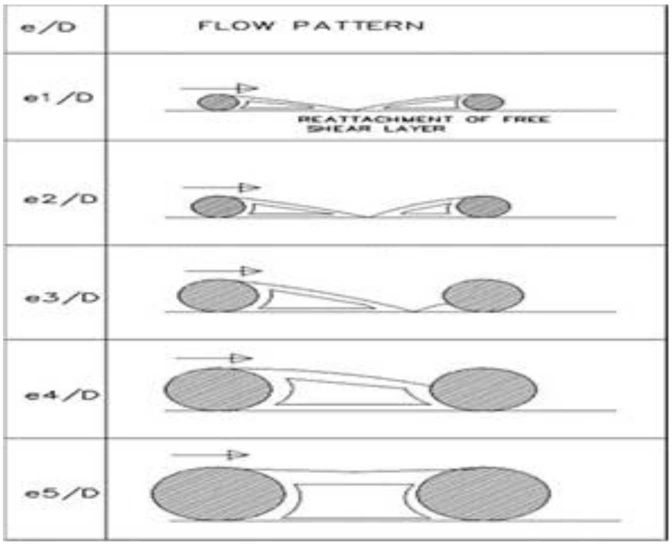

Fig: 1 Flow Pattern

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II. LITERATURE REVIEW

Roughness irregularities on thermal efficiency of solar air heaters

Nikuradase [1] (1950) analysed the effect on friction factor and velocity distribution using the pipes that were roughened by sand blasting. Nunner [2] (1958) formulated a friction similarity law and a heat momentum analogy by using sand grain roughened tubes. Several other investigations have also been carried out using the regular roughness elements in the form of cavities and ribs. Regular roughness elements are used in various shapes, arrangement and orientation over the absorber plate. Sheriff and Gumley [3] (1966) investigated by using channels and pipes having artificial roughness over the surface and reported the value of optimum roughness Reynolds number as 35. Webb *et al.* [4] (1971) investigated by creating turbulent air flow in tubes artificially roughened by rectangular repeated rib roughening and studied heat transfer and friction factor correlations for air flow in these tubes. Done and Meyer [5] (1977) and Meyer (1982) studied the effect on heat transfer and friction factor by using artificial roughness in the form of cavities and ribs. Tanasawa *et al.* [6] (1983) studied the effects on heat transfer coefficient by using three different types of turbulence promoters namely; fence type, perforated plate type and silted type and observed that among the three roughness elements used, perforated plate type was found to be more efficient in enhancing the thermal efficiency of the solar air heater. Han and Park [7] (1988) and Han et al (1989) investigated experimentally the production of turbulence in the air flow by using rib turbulators as roughness element on two opposite walls of the square and rectangular ducts and reported that angled / inclined ribs are more efficient in heat transfer as compared to the transverse ribs because in addition to breaking of viscous sub layer and producing turbulence, it also produces the secondary flow. The result also showed that narrow aspect ratio had greater efficiency than the wide aspect ratio. Lau *et al.* [8] (1991) experimentally investigated and studied the effect on heat transfer and friction characteristics by using artificial roughness as discrete ribs. It was observed that there was 10-15% increase in heat transfer coefficient by using discrete ribs having angle of attack of 90 whereas 10-20% increase was observed for inclined discrete ribs. *Han et al.* [9] (1991) further investigated the effect on thermal performance of solar air heater by using the artificial roughness in the form of V-shaped ribs over the surface of heat transferring plate and concluded that V-shaped ribs were more efficient in enhancing the heat transfer coefficient compared to the inclined and transverse ribs. Ichimiya *et al.* [10] (1991) studied the effect on heat transfer coefficient and friction characteristics in a parallel plate duct using porous type roughness on the absorber plate as these provide lower drag force as compared to the solid rib type. It was reported that porous rib type roughness provided greater thermal performance than with the solid ribs. Han and Zhang [11] (1992) carried out an investigation on effect on thermal efficiency of solar air heaters by roughening the absorber plate with parallel and V-shaped staggered discrete ribs and it was observed that increase in heat transfer coefficient was reported by V-shaped staggered discrete ribs with an angle of attack of 60̊ than the parallel discrete ribs.

Gupta *et al.* [12] (1993) used inclined circular wire ribs as turbulence promoters on the absorber plate in a rectangular duct and studied the effect of relative roughness height, angle of attack and Reynolds number on heat transfer and friction characteristics. It was observed that the maximum heat transfer coefficient and friction factor corresponded to 60̊ and 70̊ angle of attack, relative roughness height (e/D) of 0.023 and Reynolds number around 14,000.

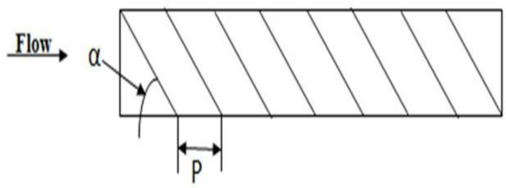

Fig. 2 Angled circular rib used by Gupta *et al.*

Verma and Prasad [13] (2000) investigated by using circular wire ribs on the absorber plate. It was reported that within the range of parameters investigated, the value of heat transfer enhancement factor varied from 1.25 to 2.08 and also for roughness Reynolds number 24 the value of thermo hydraulic performance corresponded to 71%. Momin *et al.* [14] (2002) studied the effect of V-shaped ribs on heat transfer and friction characteristics of a rectangular duct. The range of parameters covered was: Reynolds number ranging from 2500-18,000, relative roughness height of 0.02-0.034 and angle of attack 30̊ -90̊. It was reported that for an angle of attack of 60̊, the maximum enhancement of Nusselt number and friction factor was found to be 2.30 and 2.83times to the smooth surface and also for the relative roughness height of 0.034 and angle of attack of 60̊, the value of Nusselt number was enhanced 1.14 and 2.30 times to that of inclined ribs and smooth plate respectively.

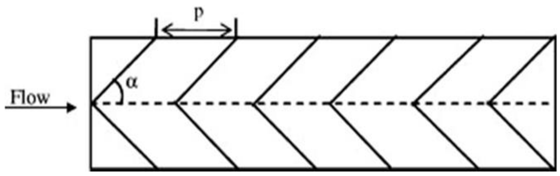

Fig. 3 Roughness geometry used by Momin *et al.*

Jaurker *et al.* [15] (2006) studied the effect of relative roughness pitch(p/e), relative roughness height(e/D_h) and relative groove position by using rib grooved artificial roughness having the range of parameters as Reynolds number (Re) 3000-21000, relative roughness height (e/D_h) 0.0181-0.0363, relative roughness pitch (P/e) 4.5-10 and groove position to pitch ratio(g/p) 0.3-0.7. It was observed that the Nusselt number increased up to 2.75 times as compared to that of the smooth duct and also the friction factor was reported to be increased up to 3.61 times in the range of parameters investigated.

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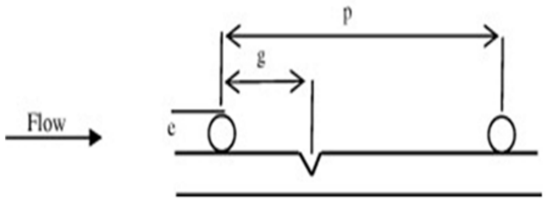

Fig. 4 Geometry used by Jaurker *et al.*

Saini and Verma [16] (2008) used dimple shaped roughness geometry on the heat transferring plate and studied the effect of relative roughness pitch (P/e) and relative roughness height (e/D_h) by taking the range of roughness parameters as Reynolds number (Re) 2000-12000, relative roughness pitch (P/e) 8-12 and relative roughness height (e/D_h) 0.018-0.037 and the increase in Nusselt number and friction factor was reported to be 1.8 and 1.4 times respectively.

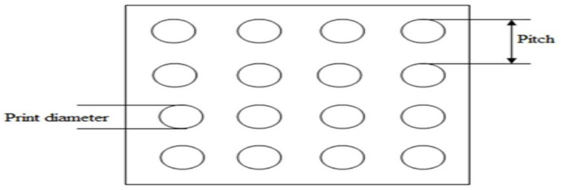

Fig. 5 Dimple shape roughness element

Layak *et al.*[17] investigated the effect of repeated transverse compound rib-groove arrangement on the heat transfer and friction characteristics on the heat transferring plate of the solar air heater. They investigated by studying four different relative groove positions values of 0.3, 0.4, 0.5 and 0.6 with range of parameters like fixed relative roughness height (e/D_h) of 0.030 and relative roughness pitch (P/e) of 10 respectively and it was reported that at relative groove position (g/p) of 0.4, maximum enhancement in Nusselt number and friction factor was observed to be 2.42 and 2.6 times respectively as compared to the smooth plate. Karmare and Tiketar [18] investigated by using metal grit ribs as roughness element and studied the effect on heat transfer and friction characteristics of the rectangular duct by covering range of parameters which involve relative roughness height ranging from 0.035-0.044, relative roughness pitch ranging from 12.5-36, Reynolds number varying from 4000-17000 and relative grit length (1/s) from 1-1.72. The range of parameters recorded that corresponded to the optimal performance were; relative grit length (1/e) having value of 1.72, relative roughness height having value of 0.044 and relative roughness pitch having value of 17.5 and the maximum enhancement in Nusselt number and friction factor was reported to be 187% and 213% respectively. Saini and Saini [19] investigated the effect on heat transfer coefficient and fluid flow characteristics of a rectangular duct by providing arc shaped ribs as artificial roughness on the heat transferring plate of the duct. The range of parameters covered were Reynolds number (Re) ranging from 2000-17000, relative roughness height (e/D_h) ranging from 0.0213-0.0422 and relative arc angle ($\alpha/90$) 0.3333-0.6666.

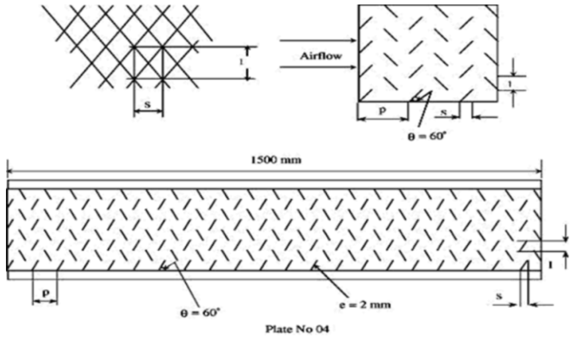

Fig. 6 Metal grit ribs used by Karmare and Tikekar

It was observed that relative arc angle ($\alpha/90$) of value 0.3333 and relative roughness height of value 0.0422 corresponded to maximum enhancement in Nusselt number and friction factor having value 3.6 and 1.75 times over that of smooth plate duct. Karwa [20] experimentally studied the effect on the efficiency of solar air heater by using 60 inclined rectangular cross-section ribs on the absorber plate. The range of parameters covered included aspect ratio (W/H) ranging from 7.19-7.75, relative roughness height ranging from 0.0467-0.050, Reynolds number ranging from 2800-15000 and relative roughness pitch having fixed value of 10. The result reported 1.65-1.90 times increase in heat transfer coefficient and increase in friction factor was reported to be 2.68-2.94 times over smooth duct. Singh *et al.* [21] investigated by heating and roughening one broad wall of the rectangular duct by periodic discrete V-down rib and the range of parameters investigated included Reynolds number varying from 3000-15000, relative gap width (g/e) ranging from 0.5-0.2, relative gap position (d/w) ranging from 0.20-0.80, relative roughness height (e/D_h) ranging from 0.015-0.043, relative roughness pitch (P/e) 4-12, angle of attack 30-75 respectively. The maximum enhancement in friction factor and Nusselt number was observed to be 3.11 and 3.04 times as compared to the smooth surface.

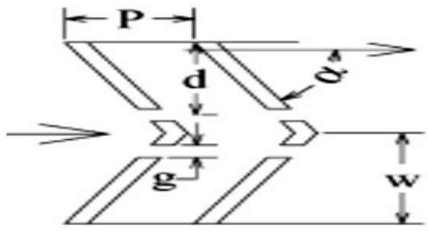

Fig. 7 Roughness geometry used by Singh *et al.*

Kumar and Bhagoria [22] provided discrete W-shaped roughness on one broad wall of rectangular duct and investigated the effect on heat transfer and friction flow characteristics of artificially roughened solar air heater. Range of parameters covered were relative roughness height (e/D_h) ranging from 0.0168-0.0338, relative roughness pitch (P/e) ranging from 12.5-36, angle of attack ranging from 30-75, Reynolds number ranging from 3000-15000. The result showed that for an angle of 60, the maximum enhancement in

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Nusselt number and friction factor was 2.16 and 2.75 times respectively as that of the smooth duct.

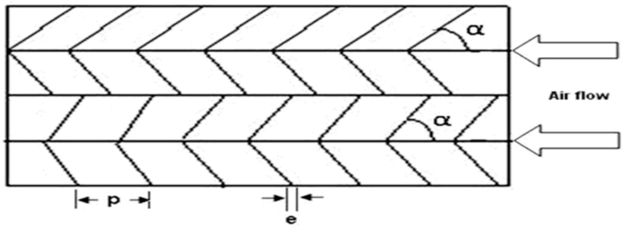

Fig. 8 Roughness geometry used by Kumar and Bhagoria

Bopche and Tandale [23] used U-shaped turbulators as roughness element on the heat transferring surface and studied its effect on the thermal efficiency of the solar air heater by investigating under range of parameters covered: Reynolds number varying from 1800-3800, relative roughness height (e/D_h) 0.0186-0.03986, relative roughness pitch (P/e) 6.67-57.14, arc angle of 90 . The result showed 2.388 and 2.50 times enhancement in Nusselt number and friction factor. Bhushan and Singh [24] investigated the effect on heat transfer and friction characteristics by providing as roughness element on the absorber plate. Range of parameters investigated were : relative short way length (S/e) in the range of 18.75-37.50, relative long way length (L/e) in the range of 25.0-37.50, relative print diameter (d/D_h) in the range of 0.147-0.0367 and Reynolds number in the range of 4000-20000 respectively. As compared to the smooth duct, the maximum enhancement in Nusselt number and friction factor was reported to be 3.8 and 2.2 times respectively.

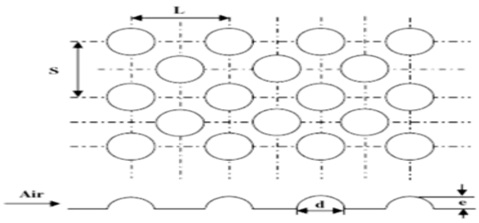

Fig. 9 Roughness geometry used by Bhushan and Singh

varun *et al.* [25] investigated the heat transfer and friction characteristics of solar air heater by using a combination of inclined and transverse ribs on the absorber plate. Range of parameters investigated were Reynolds number (Re) 2000-14000, relative roughness pitch(p/e) 3-8, relative roughness height(e/D_h) .030 and aspect ratio is 10. For relative roughness pitch (P/e) value of 8, the best thermal performance has been obtained.

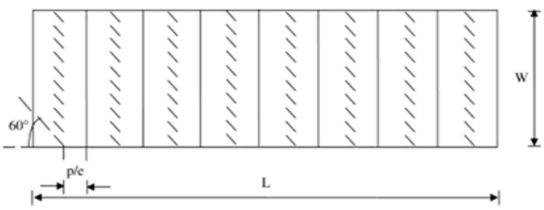

Fig. 10 Inclined and transverse ribs used by Varun *et al.*

Sahu and Bhagoria [26] used 90° broken ribs as the roughness element and studied the effect on heat transfer and friction factor for rectangular duct including parameters; roughness height (e) value of 1.5, duct aspect ratio(W/H) having value 8, pitch value varying from 10 – 30 mm and Reynolds number varying from 3000 – 12000. The roughness geometry has been shown in fig. Heat transfer coefficient was observed to be increased by 1.25 -1.4 times for the roughened heat transfer plate as compared to smooth plate.

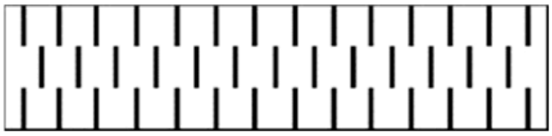

Fig. 11 Roughness geometry used by Sahu and Bhagoria

Alam *et al.*[27] studied the effect on heat transfer and friction flow characteristics of a rectangular duct by using V-shaped perforated blocks as turbulence promoters on the absorber plate. Geometrical parameters included in this experimental investigation were; relative blockage height (e/H) ranging from 0.4-1.0, relative pitch ratio (P/e) of 4-12, open area ratio (β) of 5-25% having fixed angle of attack (α) of 60°, covering range of Reynolds number from 2000-20000. The result reported that maximum enhancement in Nusselt number and friction factor was found to be of order 6.76 and 28.84 times to that of the smooth plate respectively.

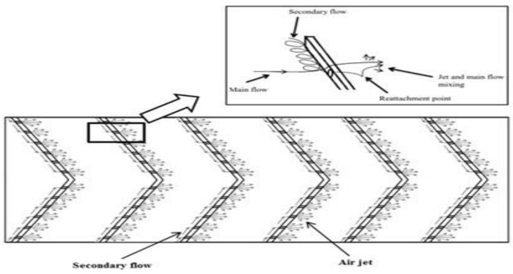

Fig. 12 Roughness geometry used by Alam *et al.*

Maithani and Saini [28] used V-ribs with symmetrical gaps as roughness element and studied the effect on enhancement of thermal efficiency of solar air heaters. Range of parameters covered included; Reynolds number varying from 4000-18000, number of gaps (N_g) 1-5, relative gap width (g/e) 1-5, relative roughness pitch (P/e) 6-12, angle of attack (α) ranging from 30-75° and relative roughness height (e/D_h) of 0.043. It was reported that maximum enhancement in Nusselt number and friction factor was of the order 3.6 and 3.67 times respectively as compared to the smooth duct.

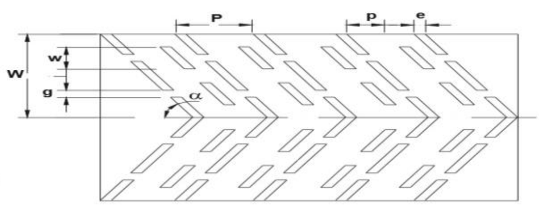

Fig. 13 Roughness geometry used by Maithani and Saini

Deo *et al.* [29] studied the effect on thermal efficiency of rectangular solar air heater duct by artificially roughening it with multi-gap V-down ribs combined with staggered ribs. The range of parameters encompassed in the investigation included; aspect ratio of 12, Reynolds number varying from 4000-12000, rib pitch to height ratio (P/e) varied from 4 to 14, rib height to hydraulic diameter (e/D_h) from 0.026-0.057, angle of attack (α) varying from 40-80°, gap width to rib height ratio (g/e) of 1, staggered rib length to rib height ratio (w/e) of 4.5, relative staggered rib pitch (p/P) of 0.65 and two number of gaps on each side of the V-leg. The maximum enhancement recorded for the Nusselt number and friction factor was 3.34 and 2.45 times respectively.

III. Conclusion

From the above discussed literature, it is clear that the enormous enhancement has been resulted when the roughness height and the pitch of optimum size and shape are used by various researchers. It is also found that the thermo-hydraulic performance can further be enhanced on a nominal penalty of friction offered to the flow of the fluid. From the literature it is clear that there is not much work done on the combination shapes of roughness and square mesh roughness ribs. This research can be further carried out to study the effect of combination of two types of roughness ribs. Also the correlations can be developed to predict the effect of various roughness pitch and height for a given flow of fluid.

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