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A Review on Artificial Roughened Solar Air Heaters

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Abstract— Artificial roughness in the form of repeated ribs is one of the effective method for improving the performance of a solar air heater ducts. Various studies have been carried out to determine the effect of different artificial roughness geometries on heat transfer and friction characteristics in solar air heater ducts. The objective of this paper is to review various studies, in which different artificial roughness elements are used to enhance the heat transfer coefficient with little penalty of friction factor. It has been found that lot of experimental and analytical studies reported in the literature.

Index Terms—Solar air heater, heat transfer, friction factor, artificial roughness.

1. INTRODUCTION

Energy is the primary and the most universal measure of all kinds work by human being and nature. Everything what happened in the world is the expression of flow of energy from one of its forms to another. Energy in various forms has played a significant role in world wide economic progress and industrialization. In view of the world's depletion of non-renewable resources reserves, which provide the major conventional source of energy, the development of non-conventional (Renewable Energy) sources has received an impetus. Every country meets its energy demand from a variety of sources. We can broadly categorize these sources are as follows:

- Commercial Sources: [fossil fuel (coal, oil, and natural gas), hydroelectric power, nuclear power, wind power]
- Non-Commercial Sources : (wood, animal wastes and agriculture wastes)

Solar energy stands out as the brightest long range promise towards meeting the continually increasing demand for energy. The amount of solar energy intercepted by the earth is many thousand times the present rate of energy consumption of all commercial energy sources put together. The major drawback with this resource is its low intensity and intermittent in nature. Even in the hottest region on earth, the solar radiation flux available rarely exceeds 1 kW/m^2. In spite of these limitations, solar energy appears to be the most promising of all the renewable energy resources. Attempts have, therefore, been made to design and develop systems to collect and utilize this resource economically.

With the rapid rise in the population and the living standards, the world seems to engulf into major crisis, called energy crisis. If this growth continues with the same pace the condition would go from bad to worse. The reverse of conventional sources of energy like coal, petroleum and natural gas are depleting at a very fast rate to fulfill the demand of the growing population. So there is a need to look for some other energy sources that could meet this growing demand. One such source is solar energy, which is cheap available in abundance. Solar energy is a huge, inexhaustible source of energy. The main source of solar energy is the Sun. Sunlight available freely as a direct and perennial source of energy provides a non-polluting reservoir of fuel. Solar energy has been utilized in many ways. Some of its thermal applications are as follows:

1. Water heating
2. Space heating
3. Power generation
4. Space cooling and refrigeration
5. Distillation
6. Drying, and
7. Cooking

2. Air Heating Collectors

Flat plate air heating solar collectors, because of their inherent simplicity, are cheap and most widely used collection devices. These have found several applications like space heating, seasoning of timber, curing of industrial products, and crop drying. A typical configuration of flat plate air heating solar collector is shown in Fig.1. A conventional solar air heating system generally consists of an absorber plate with another parallel plate below it forming a passage for air with a high width to depth ratio i.e., aspect ratio (W/H). The solar radiations pass through the transparent cover or covers and impinge on the blackened absorber plate and are then transferred to the air, flowing beneath the absorber plate, coming in contact with nearly the entire absorber surface for effective heat transfer.

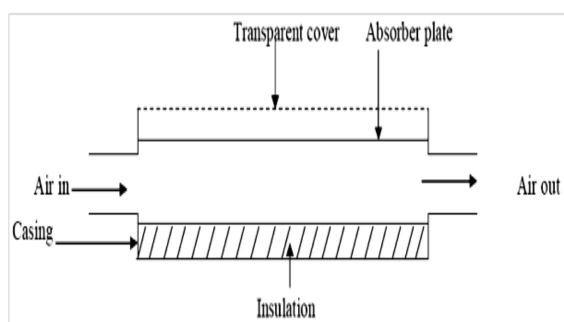

Fig. 1 Air Heating Solar Collector

3. Performance Enhancement Techniques for Solar Air Heater

The performance of a flat plate solar air collector has been found to depend strongly on the rate of incident solar radiations, the losses from the absorber surface and the rate of heat transfer from absorber plate to the air. The following are some performance enhancement techniques for solar air heaters:

3.1 Enhancement of Intensity of Solar Radiation Incident upon the Solar Collector

The performance of flat plate collectors can be significantly enhanced by addition of reflectors which increase the total collection area. Concentration ratio up to 4 and temperature up to 180°C can be achieved by providing the booster with a flat plate solar air heater.

3.2 Reduction of Thermal Losses

Following are the ways of reducing thermal losses from the solar collector;

3.2.1 By Lowering Convective as Well as Radiative Heat Loss

When collector operates at moderately high temperatures, use of two or more glass covers is a normal practice to reduce the convective and radiative heat losses and the glass reflectance can be reduced by surface treatment.

3.2.2 By Using Alternate Medium or Vacuum in the Gap Space

Convective heat losses can be minimized by optimizing the gap space and the use of alternate medium in the space between two covers. Malhotra et al. [2] have shown that the use of heavy gases can reduce the heat losses by 34%. Alternatively, partial evacuated space by 10% reduction in pressure can reduce losses by 85%. It has also been shown that a combination of moderate vacuum and a selective surface (α_s = 0.9: ε_s = 0.15) can increase the daily energy collection by as much as 278% and can make it possible to operate the collector at 150°C with a daily energy collection efficiency of more than 40%.

3.2.3 By Selective Absorber Surfaces

Selective surfaces are especially important when the collector plate temperature is much higher than the ambient air temperature, and usually maximum heat losses are through emittance from the collector surface. The maximum radiation loss appears at the wave length of about 10 microns, if the collector plate is close to room temperature and at about 5 microns if collector plate temperature is around 300°C. If the absorbing surface of the collector is treated so that it absorbs most of the solar energy between 0.3 microns and 2.5 microns and such that it emits only a small fraction of the infrared radiation, it is possible to increase the efficiency of solar energy collector, and it is possible to achieve higher temperature.

3.3 Improvement of Heat Transfer from Absorber Plate

The low heat transfer rate from absorber plate to air in the duct results in relatively higher absorber plate temperature leading to higher thermal losses to the environment. These losses can be reduced by lowering the absorber plate temperature by increasing the heat transfer coefficient between absorber and air. The ways of improved of heat transfer are discussed as follows:

3.3.1 By Providing Packed-Bed Absorbers for Air Heating Solar Collectors

Packed bed matrix absorbs solar radiation 'in-depth' and has high ratio of heat transfer area to volume and high heat transfer capability, resulting in relatively low absorber temperature. This will result in an increase in the efficiency of the collector. Enhancement of efficiency up to 60% at low flow rate (of the order of 0.018 kg/m^2) to about 45% at high flow rates (of the order of 0.04 kg/m^2) has been reported. Absorbers having a bed packed with slit and expanded aluminum foil matrix, wire screen matrix, hallow spheres and crushed glass matrices have been reported. The major disadvantages of this type collector include the high initial cost and large pumping power requirements as compared to conventional solar air heaters.

3.3.2 By Increasing the Area of Heat Transfer without Effecting the Convective Heat Transfer Coefficient

Such surfaces are termed as 'extended surfaces', i.e. corrugated surfaces and fins etc. Bevill and Brandt [3] described a solar air collector that consisted of 96 parallel and uniformly spaced aluminum fins placed below the glass cover plate. The collector was designed to obtain high collector efficiency, with low pumping power to pass air through the collector. The results indicated that the efficiency of more than 80% could be obtained with the absorber having special fins.

3.3.3 By Increasing Convective Heat Transfer Coefficient Using Artificial Roughness

In order to attain higher convective heat transfer coefficient it is desirable that the flow at the heat transfer surface should be turbulent. However, energy for creating turbulence has to come from the fan or the blower and excessive turbulence means excessive power requirement. It is therefore, desirable that the turbulence must be created only very close to the surface i.e. in laminar sub-layer only, where the heat exchange takes place and the core of the flow is not unduly disturbed to avoid excessive losses. This can be achieved by using roughened surfaces on the underside of the collector surface from where air flows. Use of artificial roughness seems to be an attractive proposition for improving the heat transfer coefficient. Artificially roughened absorber plate is considered to be good methodology to breaking the laminar sub-layer in order to reduce thermal resistance and to increase heat transfer coefficient.

4. Different types of roughness geometries in solar air heaters

There are a lot of geometries have been used in the solar air heaters on the underside of the absorber plate some of the researchers and their geometries have been in the Table 1.

Table 1: Different types of roughness geometries with different parameters having maximum heat transfer value

Author	Roughness geometry	p/e (maximum heat transfer)	e/D_h (maximum heat transfer)
Prasad and Saini[4]	Wire	10	0.033
Karwa et al.[5]	Chamfered rib	7.09	0.0441
Momin et al.[6]	V-shaped rib	10	0.034
Bhagoria et al.[7]	Transverse wedge	7.57	0.033
Jaurker et al.[8]	Transverse rib-grooved	6	0.036
Karmare and Tikekar[9]	Metal grit rib roughness	17.5	0.044
Layek et al.[10]	Transverse chamfered	6	0.04

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	rib-grooved		
Saini and Verma[11]	Dimple-shape roughness	10	0.0379
Saini and Saini[12]	Arc shaped wire	10	0.422
Varun et al.[13]	Inclined and transverse ribs	8	0.030
Soi et al.[14]	K shaped ribs	8.3	0.029
Sethi et al.[15]	Dimple shape	10	0.035
Sharma et al.[16]	V-shaped ribs	8	0.043
Kumar et al.[17]	V-shaped rib with gap	8	0.043

5. Concept of Artificial Roughness

In order to attain higher heat transfer coefficient, it is desirable that the flow at the heat-transferring surface is to be made turbulent. Surface roughness is one of the first active techniques to be considered as means of augmented forced convection heat transfer. However, energy for creating such turbulence has to come from the fan or blower and this excessive turbulence leads to excessive power requirement to make the air flow through the duct. It is therefore desirable that the turbulence must be created only in the region very close to the heat transferring surface i.e. in the laminar sub-layer region only where the heat exchange takes place and the flow should not be unduly disturbed so as to avoid excessive friction losses. This can be done by keeping the height of the roughness element to be small in comparison with the duct dimensions. Although there are several parameters that characterize the arrangement and shape of the roughness, the roughness element height (e) and pitch (p) are the most important parameters. These parameters are usually specified in terms of dimensionless parameters, namely, relative roughness height, e/d (the ratio of height of roughness element to the equivalent diameter of the duct) and the relative roughness pitch, p/e (the ratio of pitch to height of roughness elements). The roughness elements can be two dimensional ribs or three dimensional discrete elements, transverse or angled ribs or continuous or broken ribs. Although square ribs are the most commonly used geometry but chamfered, circular, semi-circular and grooved sections have been investigated in order to get most beneficial arrangement [18].

Some important geometries and the parameters that characterize the geometry and substantially influence the performance are given in Table 2.

Table 2: Different rib geometries and important parameters

S.No.	Rib Geometry	Parameters
1.	Transverse ribs	e/d , p/e
2.	Continuous Angled ribs	e/d, p/e, α
3.	V-shaped ribs	e/d, p/e, α
4.	Angled ribs with gaps	e/d, P/e, α, g/p, d/W
5.	Transverse-chamfered ribs	e/d, p/e, ϕ
6.	V-shaped staggered discrete ribs	e/d, p/e, α, B/S, p′/p, S′/S
7.	Grooved- ribs arrangement	e/d, p/e, g/p
8.	Arc shaped ribs	e/d, p/e, α
9.	W-Shaped discrete ribs	e/d, p/e, α
10.	Wire mesh	e/d, p/e, L/e, S/e

6. Effect of Rib

The most important effect produced by the presence of a rib on the flow pattern, is the generation of two flow separation regions, one on each side of the rib. The vortices so generated are responsible for the turbulence and hence the enhancement in heat transfers as well as in the friction losses takes place. A considerable influence of the presence of ribs is seen, the effect being more pronounced in turbulence intensity distribution.

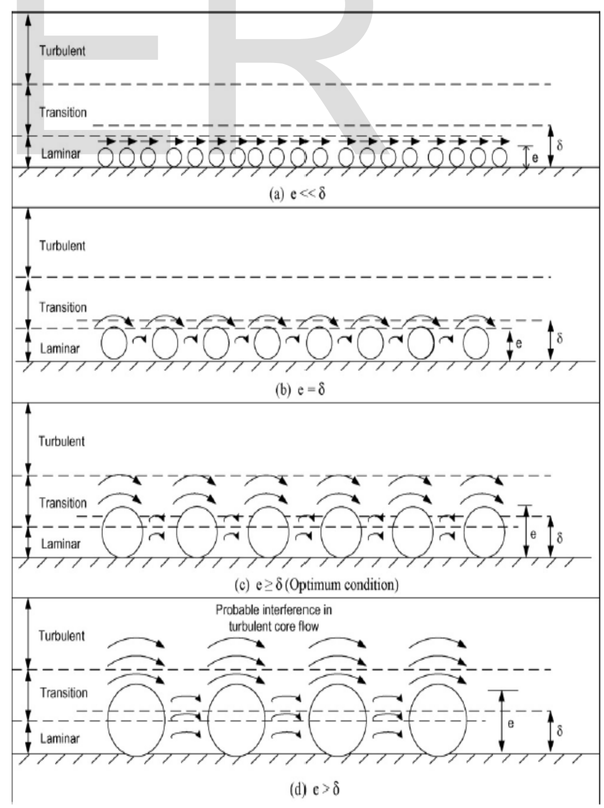

Fig. 2 Effect of Rib Height on Laminar Sub Layer [19]

7. Effect of Relative Roughness Pitch

Fig. 3 shows the flow pattern as a function of relative roughness pitch. Due to flow separation downstream of a rib, reattachment of the shear layer does not occur for a pitch ratio of less than about 8. Maximum heat transfer has been found to occur in the vicinity of a reattachment point. For relative roughness pitch considerably less than about 8, the reattachment will not occur at all resulting in the decrease of heat transfer enhancement. However, an increase in pitch beyond about 10 also results in decreasing the enhancement.

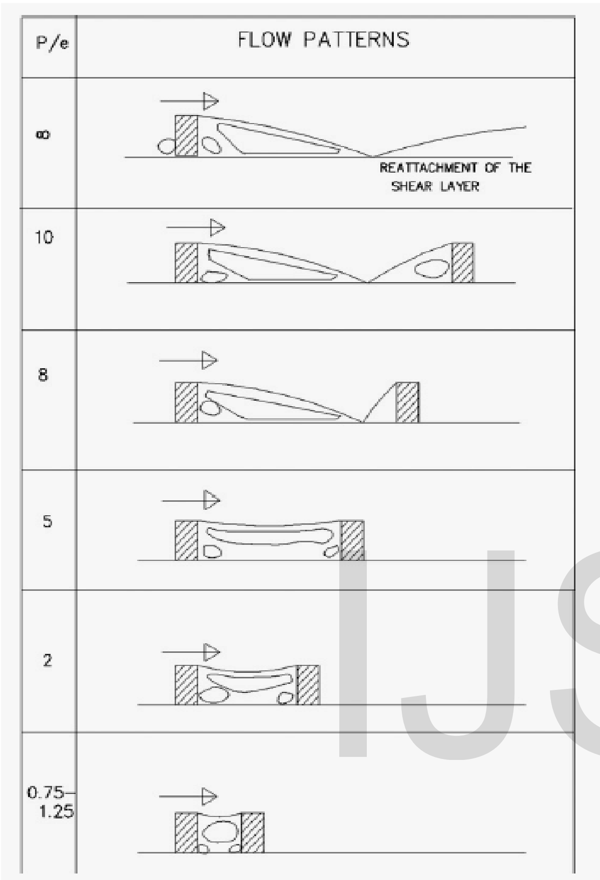

Fig. 3 Flow pattern as a function of relative roughness pitch [19]

8. Effect of Relative Roughness Height

Fig. 4 shows the flow pattern as function of relative roughness height. As relative roughness height increases, both the friction factor and Nusselt number increases. The rate of increase of average friction factor increases whereas the rate of increase of average Nusselt number decreases, with the increase of relative roughness height. At very low Reynolds number the effect of relative roughness height is insignificant on enhancement of Nusselt number. If the roughness height is less than thickness of laminar sub-layer then there will not be any enhancement in heat transfer, hence the minimum roughness height should be of same order as thickness of laminar sub-layer at the lowest flow Reynolds number. The maximum rib height should be such that the fin and flow passage blockage effects are negligible.

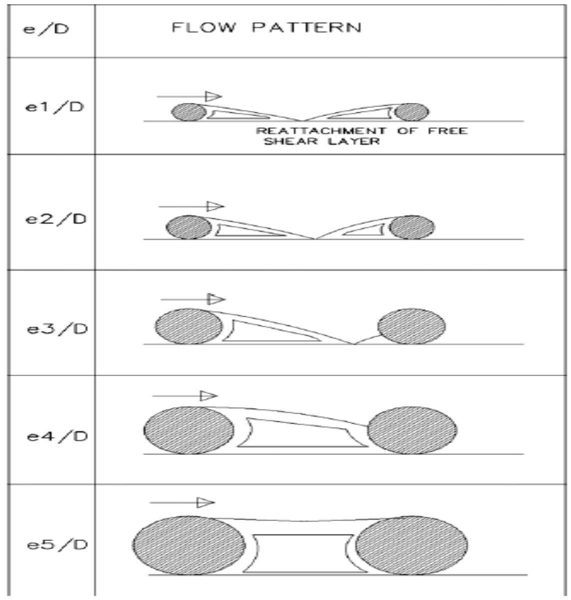

Fig. 4 Flow pattern as a function of relative roughness height [19]

The use of artificial roughness in solar air heaters owes its origin from the several investigations carried out in connection with the enhancement of heat transfer in nuclear reactor, cooling of gas turbines blades and electronics equipment. These are few important geometries used in above mention application are given in Figs 5-7.

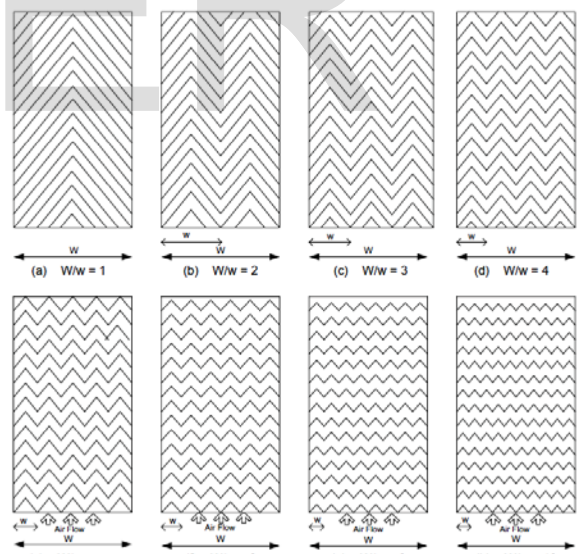

Fig. 5 Multiple V ribs geometry on absorber plate [20]

Han et al. [20] investigated the effect of the rib orientation angle on the local heat transfer distribution and pressure drop in a square channel with two opposite rib roughened walls. They observed that the V-shaped ribs shows better heat transfer compared to that of the angled ribs because of the development of two vortices cells in place of only one cell in case of inclined ribs.

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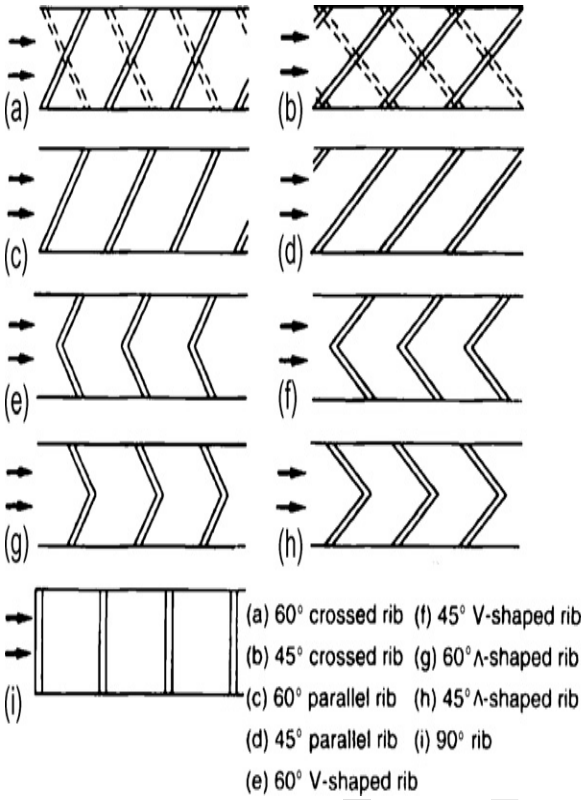

Fig. 6 Different configuration of Ribs used by Han and Zhang [21]

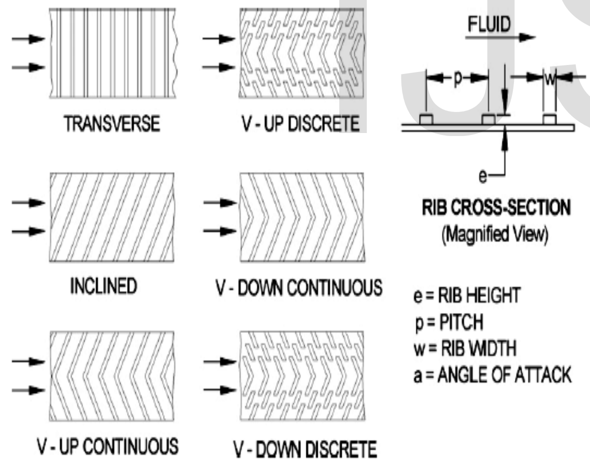

Fig. 7 Different configuration V-Shaped Ribs [22]

9. Computational analysis (CFD)

Now a days, CFD analysis is considered to be relative tools to analysis the fluid flow and heat transfer characteristics in various systems. Investigators, carried out CFD based analysis in artificially roughened duct which are presented as below:

Chaube et al. [23] carried out a CFD analysis using Fluent 6.1 software to investigate flow and heat transfer characteristics of two-dimensional rib roughened rectangular ducts with one wall subjected to uniform heat flux of 1100 W/m^2. They used SST K-ω turbulence model for analyzing the performance of nine different roughness elements and compared the predictions on the basis of heat transfer enhancement, friction characteristics and performance index.

Kumar and Saini [24] analyzed the effect of arc shaped roughness geometry on heat transfer and friction by CFD. The results obtained from different models of computational analysis were compared with Dittus-Bolter empirical relationship for smooth duct and it was found that the Renormalized (RNG) k-epsilon model had least variation as compared to other CFD models.

Karmare and Tikekar [25] used CFD to analysis heat transfer and friction characteristics of a rectangular duct having absorber plate roughened with a metal grit ribs of circular cross-section and the roughness geometry.

10. Conclusions

On the basis of the review 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. Different types of roughness geometries used by investigators are made by fixing wires by any adhesive, rib formation by machining process, expanded metal mesh ribs and creating dimple shaped geometry. A lot of work is also in progress with the computational methods (CFD) by different researchers.

***Nomenclature**

E	rib height
D_h, d	hydraulic diameter of duct
W	width of duct
H	height of duct
P, p	wire pitch
B	half length of full V-rib element
L	length of test section of duct or long way length of mesh
S	length of discrete rib
(p/e)	relative roughness pitch
(e/D_h), (e/d)	relative roughness height
(W/H)	Aspect ratio
B/S	relative roughness length
d/W	relative gap position
S/e	relative short way length of mesh
L/e	relative long way length of mesh
g/p	relative groove position
α	angle of attack
ϕ	rib chamfer/wedge angle
ε_s	Emmisivity of selective surface
α_s	Absorptivity of selective surface

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