Enhancing the Thermal Energy Transfer in a Solar Air Heater's Duct by Introducing Artificial Surface Roughness: A Review

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Abstract:- In the study of heat transmission, artificial roughness is crucial. It offers a smooth absorber plate surface to boost the airflow turbulence across it. Artificially applied roughness additionally increase the absorber plate's surface area and produce vortices and eddy in the airflow, which raises the air's heat transfer coefficient. Varied artificial roughness with varied forms and geometries has different heat transmission rates. In the current study, different artificial roughness components employed in solar air heater ducts were studied. This paper's goal is to investigate how artificial roughness components affect heat transfer rates with minimal frictional cost. Tabulated forms of developed Correlations proposed by various authors for heat transmission and frictional factor are given. The present article gives immense support to researchers who are researching new artificial roughness for enhancing the heat transmission rate in solar air heater ducts and comparing different artificial roughness that are already studied.

Keywords: *Solar air heater duct, artificial roughness, convective heat transmission coefficient, frictional factor.*

I. INTRODUCTION

Energy has come to play a critical role in many global economic advancement and industrialization processes. In the historical era of energy scarcity, the non-renewable energy supplies are fixed. Therefore, it is important to give upgrading and employing sustainable power source assets more thought. The sun is unquestionably a source of energy. The sun is the source of all known energy patterns in the cosmos. The best benefits of solar energy are that it is clean and can be produced without harming the environment, as opposed to other types of energy. [1]By adding roughness to an absorber's bottom in the form of ribs, grooves, baffles, winglets, twisted tapes, etc., conventional solar air heaters can increase their thermal efficiency. A passive method of heat transmission known as artificial roughness can be used to increase the thermo hydraulic performance of a solar air heater. At the absorbing surface, the gadget is known as a solar air heater since it turns solar energy into thermal energy.By adding various roughness components to the surface of the absorber plate, numerous techniques have been developed by numerous researchers to increase heat transfer through these solar air heaters. This study examines the heat transfer coefficient and friction factor association that numerous researchers have created for solar air heaters with roughened ducts. This paper compiles all of these attempts to reach a conclusion about earlier experimental works. Researchers have the opportunity to develop new parameters using new materials and techniques to achieve an improvement in heat transfer with a reduction in friction power provision. [2].

A traditional solar air heating system is made up of seven components: a supply duct, an exit duct, an absorbing tray, glass, a rigid frame, insulation, and a solid block of wood. A glazing setup is provided on the upper surface to absorb more solar energy. The highly thermally conductive solar absorber panel catches the solar energy that enters the glass and regulates how effectively heat is delivered to the heated air. The glazing materials acrylic, tempered glass, polycarbonate, and others are widely used [3]. The construction and material used to make the absorber plate will determine how well it performs. Because of its low weight, high strength, and ease of fabrication, a specific alloy of aluminium is commonly selected [4].

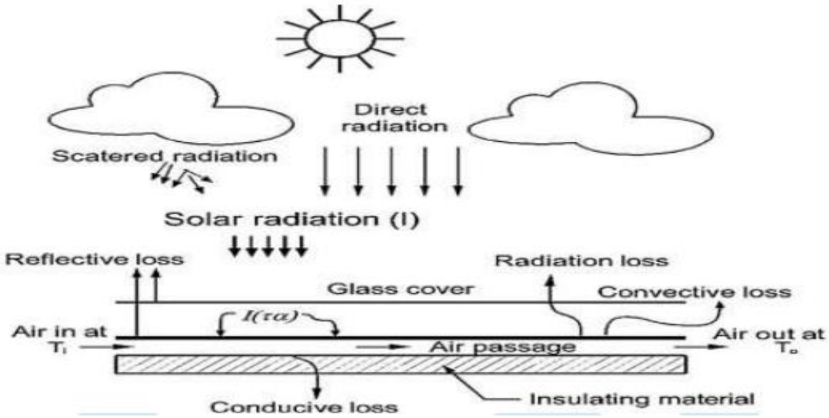

Fig. 1: Conventional Solar Air Heater[2]

II. CONCEPT OF ARTIFICIAL ROUGHNESS

Solar air heaters are tools that use the sun's energy to generate heat that can be used for a variety of tasks, including drying, preheating air for industrial processes, and room heating. Making the most of the heat transmission from the absorber plate to the air passing over it is one of the issues faced by solar air heaters. Artificially roughening the surface of the absorber plate is one method for improving heat transfer in solar air heaters. By including minor obstructions or features on the surface of the absorber plate, artificial roughness is produced. These characteristics cause turbulence and disrupt airflow, which raises the heat transfer coefficient and enhances overall heat transfer. Solar air heaters can use a variety of artificially textured surfaces. Ribbed surfaces, dimpled surfaces, and perforated surfaces are a few examples. The absorber plate can be given ribbed surfaces by adding longitudinal or transverse ribs. The absorber plate is given circular or elliptical dimples to produce surfaces with dimples. Small holes are drilled into the absorber plate to produce perforated surfaces. The choice of artificial roughness is influenced by a number of variables, including air flow rate, air temperature, and the shape of the solar air heater. By deciding on the right kind of artificial roughness, the performance of the solar air heater can be maximized .Overall, the use of artificial roughness is a promising technique to enhance heat transfer in solar air heaters, and it has the potential to improve the efficiency and performance of these devices.

To evaluate the effectiveness of artificial roughness to increase the rate of transference of heat in solar air heaters, several basic geometrical dimensionless parameters are often utilized. These parameters include:

A. *Relative roughness pitch*$(\boldsymbol{p/e})$:

A characteristic that describes the geometry of artificial roughness elements in a channel or duct is called relative roughness pitch. It is a dimensionless number that represents the ratio of pitch to height of the roughness component in respect to the hydraulic diameter of the duct. It is, in other words, the ratio of the height of the rib to the separation between its neighbouring ribs. The value of relative roughness pitch for various artificial geometries is shown in Table 1 as a result of research into how relative roughness pitch influences flow patterns and heat transfer coefficients.

Table 1: Relative roughness pitch (P/e) values at which the heat transfer coefficient is at its highest for various roughness geometries used in solar air heater ducts

Investigators	**relative roughness pitch value at which the heat transmission coefficient is at its highest** $(\boldsymbol{P/e})$	**Roughness geometry**
Prasad and Saini [5] [1988]	10	Wire
Sahu et al. [7][2005]	13.33	90°Transversebroken wire ribs
Saini and Saini[8][2008]	10	Arc Shape ribs
Lanjewar et.al[9][2011]	10	W-shape ribs
Aharwal et al.[10][2008]	10	Inclined with gap ribs
Jaurker et al. [11] [2006]	6	Transverse rib-grooved
Saini and verma[12][2008]	8-12	Rib dimpled ribs
Chamoli and Thakur[13][2016]	1-4	Perforated V-baffles
Varun et.al[14][2008]	8	Inclined and Transverse ribs

The flow patterns downstream of a rib are shown in Figure 2 (Prasad & Saini, 1988) as a function of the relative roughness pitch. Reattachment of the free shear layer does not happen with a relative roughness pitch (p/e) of less than about 8 to 10 due to separation at the rib. The area next to the reattachment point has the highest heat transfer coefficient. Reattachment won't take place for relative roughness pitch (p/e) values between 8 and 10, which lowers the rate of heat enhancement. With a drop in pitch, the friction factor will grow more quickly. However, the augmentation of heat transmission decreased as relative roughness pitch (p/e) increased beyond 10.

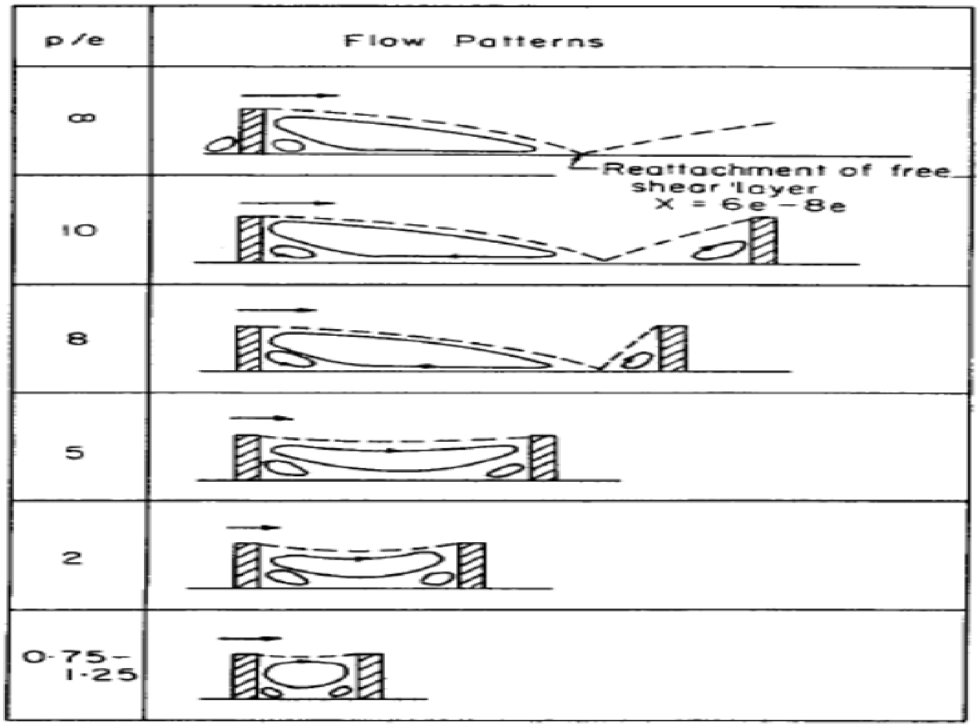

Fig. 2: Based on the degree of roughness as a measure of Pitch relative roughness pitch, Prasad and Saini (1988) [5] depicts the patterns of ribs flowing downward.

B. Relative roughness height($\boldsymbol{e/D}$)*:*

Engineers use the relative roughness height, a dimensionless metric, to characterize the geometry of the parts having a rough surface in a conduit or channel. The height relative roughness is represented by the ratio of the height of the roughness elements to the conduit hydraulic diameter, denoted as (e/D), where e is the height of the roughness components and D is the conduit hydraulic diameter. The relative roughness height is a crucial factor to take into account when designing roughness components in order to maximize thermal transfer and acceptable levels of turbulence while minimizing pressure drop and energy consumption.

Figures 3a and 3b (Prasad & Saini, 1991) specifically depict the effects of varying rib height on the rib's uniform sub-layer and its downstream component. A localized wall disturbance results from repetitive ribs that split the viscous sub-layer and speed up heat transmission. If the ribs extended past a viscous sub-layer, the rate of heat transmission would increase, but friction losses would also increase. In order to achieve the best thermo hydraulic performance, the roughness height should be considerably more important than the thickness of the sub-layer of transitioning (Prasad & Saini, 1991). Table 2 displays the numerical information of relative roughness height (e/D) for the maximum heat transfer coefficient.

Table 2: The values of the relative roughness height (e/D) at which the heat transmission coefficient is at its highest for various roughness geometries used in solar air heater ducts

Investigators	**Roughness geometry**	**Maximum heat transfer coefficient $(\boldsymbol{e/D})$ value for relative roughness height**
Prasad and Saini[5] (1988)	Wire	0.033
Sahu et al. [7][2005]	90°Transversebroken wire ribs	e=1.5mm
Saini and Saini[8] (2008)	Arc shaped wire	0.0422
Lanjewar et.al[9][2011]	W-shape ribs	0.03375
Aharwal et al.[10][2008]	Inclined with gap ribs	0.037
Jaurker et al. [11](2006)	Transverse rib-grooved	0.036
Saini and verma[12][2008]	Dimpled shape ribs	0.037
Chamoli and Thakur[13][2016]	Perforated V-baffles	0.6
Varun et.al[14][2008]	Inclined and Transverse ribs	0.030

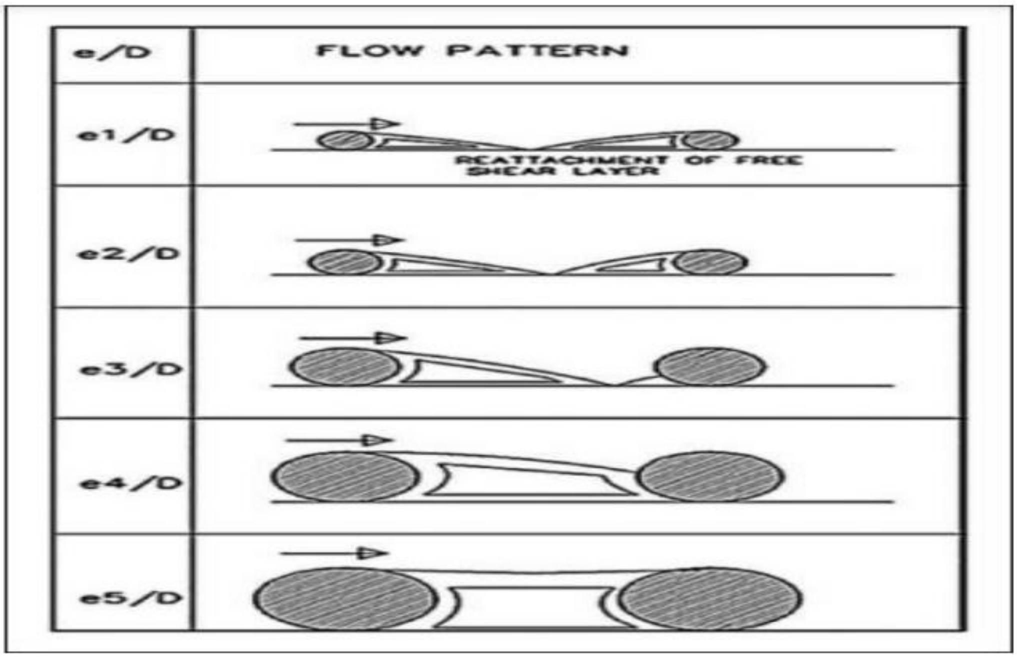

Fig. 3(a) by Prasad and Saini (1988) shows the flow patterns around the wires and roughness as a measure of the corresponding roughness height. [5]

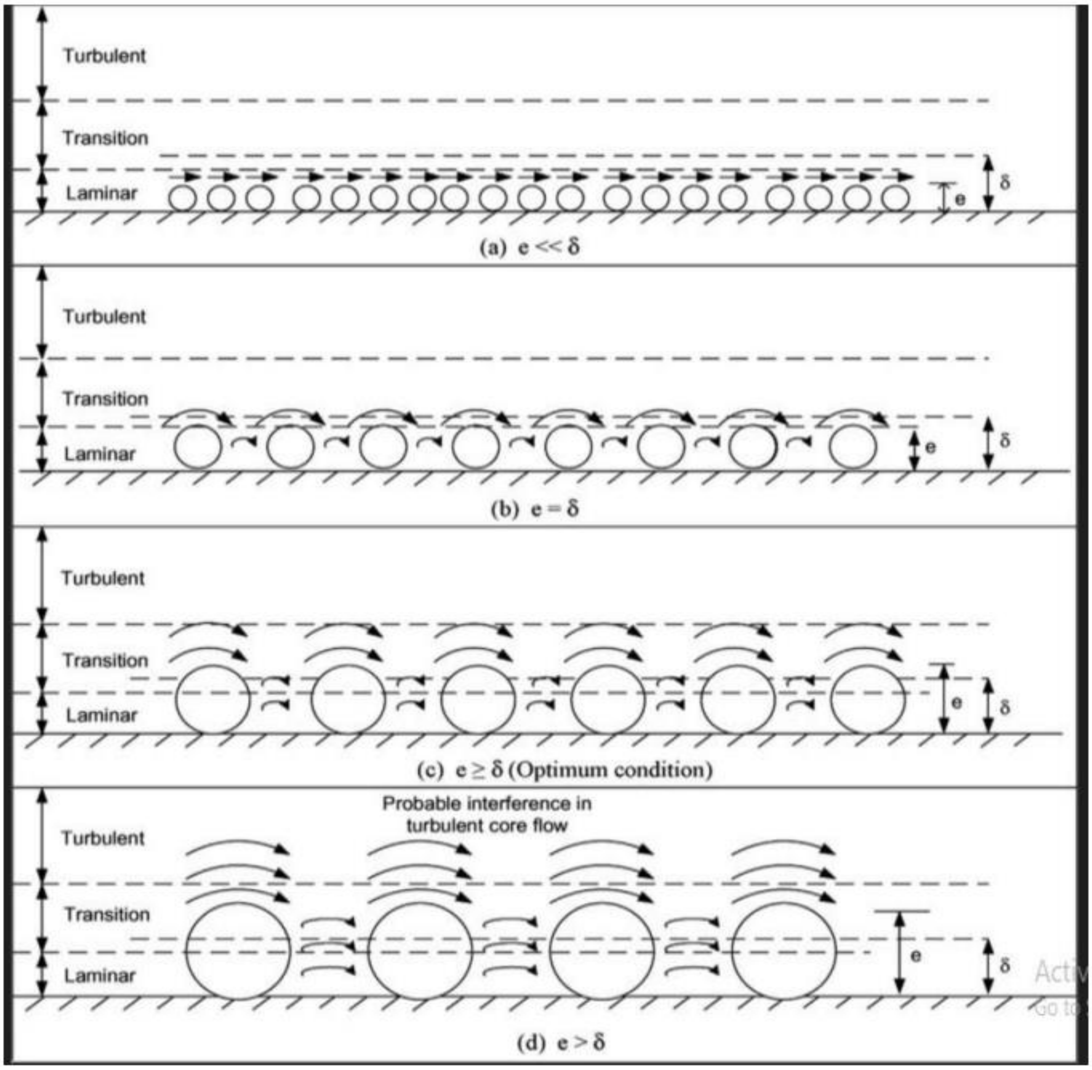

Fig. 3(b): Illustrates the roughness height in relation to a laminar sub layer by Prasad & Saini (1991) [6].

C. Angle of attack:

The angle of attack is used to define the direction of fluid flow when it comes into contact with roughness elements on the surface while discussing the impact of artificial roughness on solar air heaters. The improved heat transmission and turbulence in the duct may be impacted by this orientation. Depending on the system design, the roughness elements are frequently positioned at particular angles with respect to the flow direction. The fluid flows' degree of disturbance and mixing, and consequently the system's loss of pressure and thermal transfer coefficient, can be affected by the angle of attack. The angle appears to have the greatest impact on the pattern, according to study done to assess the effect of rib alignment.Heat can be transported more quickly via inclined ribs than through transverse ribs because of the extra flow that the inclined ribs produce, which also breaks up the viscosity sublayer and causes localized wall turbulence conditions.

Table 3 displays the angle of attack values (α) for the greatest heat transfer coefficient for several artificial roughness types.

Table 3: demonstrates the maximum heat transfer coefficient for several types of artificial roughness at its angle of attack (α).

Investigators	**Roughness Geometry**	**Range of values for the maximum heat transfer coefficient (α)**
Prasad and Saini[5] (1988)	Wire	-
Sahu et al. [7][2005]	90°Transversebroken wire ribs	90°
Saini and Saini [8](2008)	Arc shaped wire	$(\alpha/90)$
Lanjewar et.al[9][2011]	W-shape ribs	30°-75°
Aharwal et al.[10][2008]	Inclined with gap ribs	60°
Jaurker et al.[11] (2006)	Transverse rib-grooved	-
Saini and verma[12][2008]	Rib dimpled ribs	-
Chamoli and Thakur[13][2016]	Perforated V-baffles	-
Varun et.al[14][2008]	Inclined and Transverse ribs	60°

III. SHAPE OF ROUGHNESS ELEMENTS

Depending on the configuration and usage circumstances, the artificially roughed elements used in solar air heaters can assume a variety of shapes. However, their primary mode of function is to agitate the fluid flow, which quickens heat transfer and increases thermal efficiency. The shape and alignment of the roughness features can significantly affect the system's stream characteristics, radiation transfer, and pressure reduction. The shape and alignment of the roughness components must be carefully designed to achieve the highest possible thermal performance and efficiency.

The following research looked at how the design of roughness elements used to produce artificial surface abrasion to enhance the air heating system powered by solar energy impacts the Reynolds number and Nusselt number:

A. Small diameter protrusion wires:

An experiment was conducted by Prasad et al. in 1988 [5] to determine how the height affects the thermal transfer coefficient and friction value of completely formed turbulence.

In a solar-powered duct air warmer, relative roughness height (e/D) and relative roughness pitch (p/e) were measured. The minuscule diameter protrusion wires for the conduit from the absorbent plate are shown in Figure 4. It was discovered that an average Nusselt number in the rough conduit was 2.10, 2.24, 2.38 and 3.08, 3.67, 4.25 times bigger than in the smoother conduit for height relative roughness of 0.020, 0.027, and 0.033.

In comparison to the smoother duct, the average Nusselt value and frictional value increased by almost 2.38, 2.14, 2.01, and 4.25, 3.39, 2.93 times, respectively. The comparable values for relative roughness pitch of 10, 15, and 20 are 2.38 and 4.25, which are significantly higher than those for a duct that is smoother. These were the largest advancements in friction value and heat coefficient of transmission.

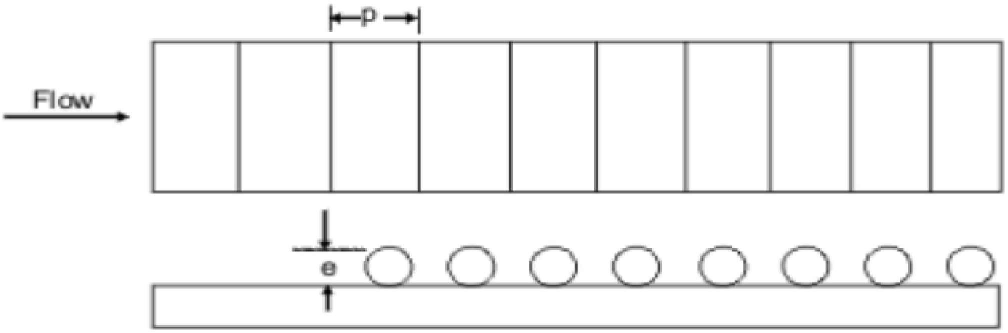

Fig. 4: Prasad and Saini (1988) [5] analyze the form and orientation of a texture element.

B. 90° broken transverse ribs:

The effect of rib pitch on the rate of thermal transfer and friction Values for 90° divided transversal ribs with a rib depth of 1.5 mm and an aspect ratio of 8 were assessed in a study by Sahu and Bhagoria in 2005 [7]. Fig 5 presents the findings. The margins at the extremities of the ribs also experienced division as the pitch was increased from 10 to 30, resulting in an auxiliary stream that prevented the boundary layer from advancing into the nearby connection zone.

The greatest Nusselt value was attained at a roughness pitch p of 20 mm; as roughness pitch rose, it decreased.

The investigators concluded from their test results that the efficiency of the textured solar power air heater varied depending on the flow conditions. The highest level of thermal efficiency was between 51% and 83.5%. Using a 20 mm pitch, the best thermal efficacy of 83.5% was attained.

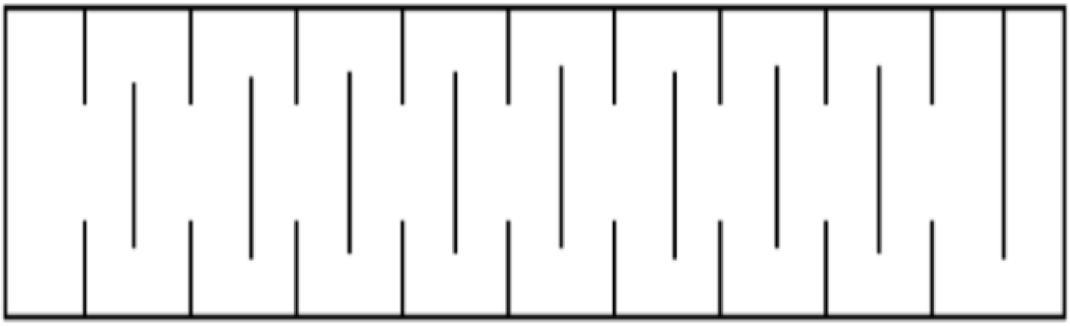

Fig. 5: Shows transverse ribs that have established by Sahu and Bhagoria in 2005 [7]

C. Arc Shaped ribs:

In order to ascertain the effects of the arc-shape parallel wire's relative roughness height (e/d) and relative angle of attack $(\alpha/90)$ on the heat transfer coefficient and friction factor, Saini and Saini (2008) [8] conducted an experimental investigation. The figures 6 and 7 demonstrate these findings. A relative arc angle $(\alpha/90)$ of 0.3333 at a relative roughness height of 0.0422 leads to the biggest Nusselt number enhancement, which was 3.80 times. But it was discovered that these qualities were only related to a 1.75 times increase in the friction factor.

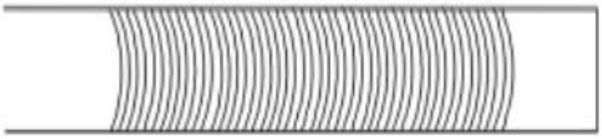

Fig. 6: Saini and Saini (2008[8] explored the type and orientation of the roughness element.

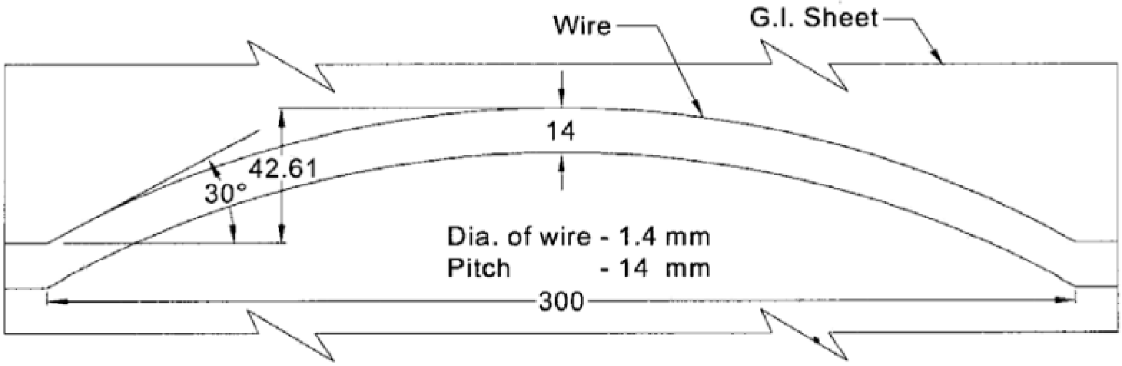

Fig. 7: Saini and Saini's (2008)[8] investigation of the type and direction of roughness elements

D. W-Shape ribs:

Figure 8 shows the W-shaped rib artificial roughness element that Lanjewar et al. (2011) [9] used in their experiment to measure the homogeneity of the heat flux in a turbulent flow.The friction and heat transfer coefficients were computed experimentally for a Reynolds value range of 2300–14,000 using air as the working fluid. It was discovered that when the Reynolds value grew, the Nusselt value increased but the frictional value decreased. Furthermore, it was shown that W-down ribs outperformed W-up and Vribs in terms of thermo-hydraulic performance. The highest thermo-hydraulic efficiency was determined to be 1.98 for W-down ribs for the range of parameters assessed, compared to 1.81 for W-up ribs.

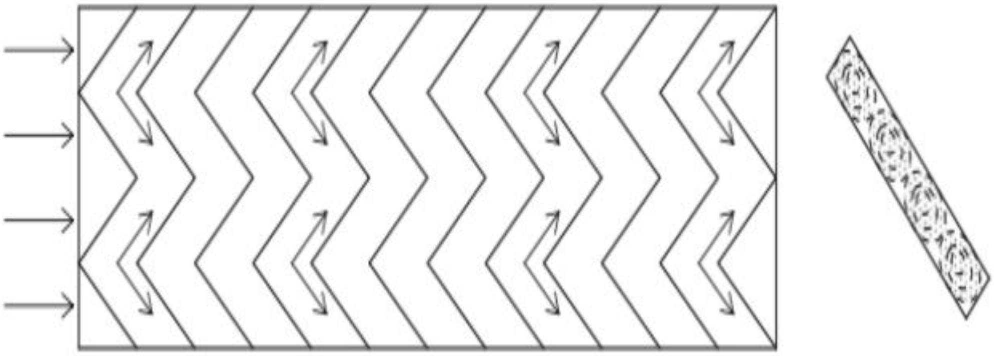

Fig. 8: W-shaped texture structure by Lanjewar et al. [9]

E. *Inclined with gap ribs:*

Aharwal et al. (2008) [10], as shown in Fig. 9, investigated the effects of the gap to width ratio (g/e) and gap to position ratio (d/W) in an inclined split rib arrangement in a rectangular duct of a solar air heater. Heat transfer was improved and friction was reduced by the space between the slanted ribs. The Nusselt number and friction factor rose over the smooth duct by 1.48 to 2.59 and 2.26 to 2.9 times, respectively. The Nusselt number, friction factor, and thermo-hydraulic performance were found to be at their highest values for the inclined repeating rib gap, which had a relative gap position of 0.25 and a relative gap width of 1.0**.**

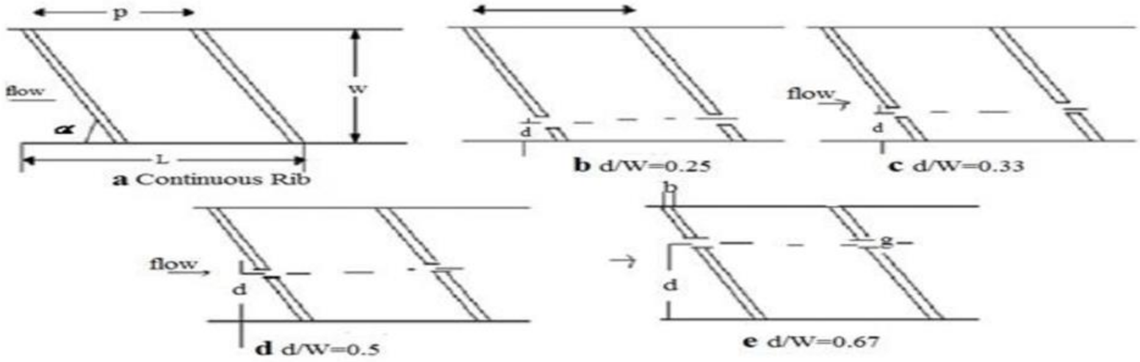

Fig. 9: Inclined with Gap Ribs by Aharwal et al.[10]

F. *Transverse rib-grooved:*

The findings of a study by Jaurker et al. (2006) [11] to ascertain the impacts of the relative roughness pitch , height relative roughness height , and associated groove alignment on the coefficient of transmission and friction value of rib-grooved artificial roughness are shown in Figure 10. The experiment found that at a relative roughness pitch of around 6, the transmission of heat increased to its maximum level, and at either end of this pitch, it decreased. A groove alignment to pitch ratio of 0.4 was discovered to be the optimal circumstance for heat transfer when compared to a smooth duct. Within the parameters examined, the inclusion of rib-grooved artificially roughened improved the Nusselt value by 2.7 times while raising the frictional value by 3.6 times.

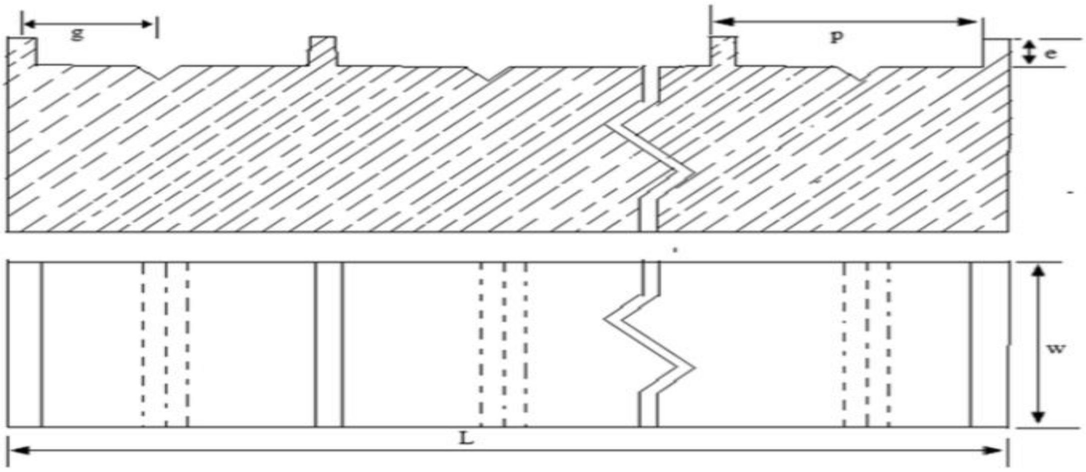

Fig. 10: shows the nature and location of the surface roughness component as explored by Jaurker et al. (2006) [11].

G. *Dimpled shape ribs:*

Saini et al. (2008) [12] investigated the effects of heat transfer and friction factor on the relative roughness height (e/D) and relative roughness pitch (P/e) of the dimple shape roughness geometry. It was discovered that the inclusion of dimple-shaped roughness geometry could have a significant positive impact on the absorber plate of a solar air heater duct.

It has been demonstrated that the Nusselt number can reach a maximum value of 10 for relative pitch (p/e) and 0.0379 for relative roughness height (e/D). While it has been shown that the relative pitch (p/e) of 10 and the relative roughness height (e/D) of 0.0289, respectively, correlate to the lowest value of the friction factor**.**

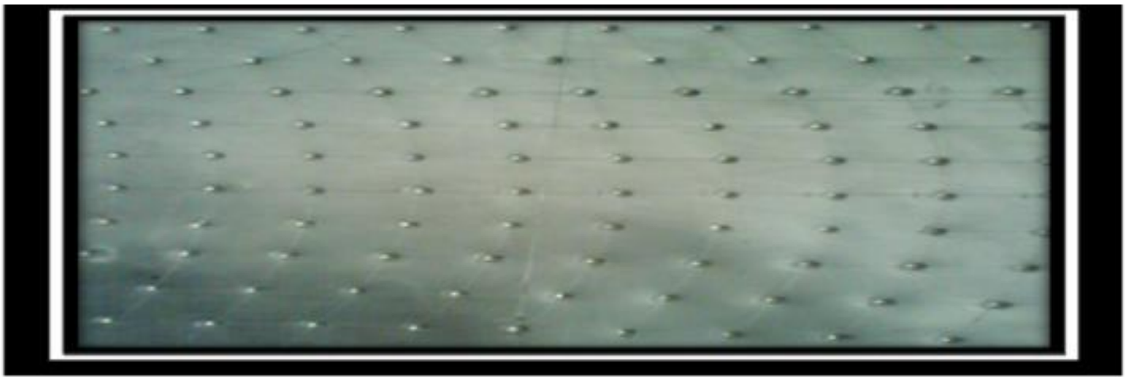

Fig. 10: Dimple Shaped Ribs by Saini et al. [12]

H. *Perforated V-baffles:*

The effectiveness of a roughened duct solar air heater with V-down perforated baffles on the air flow side of the absorber plate was investigated by Chamoli et al. (2013) [13].It is desirable to run the system within this range in order to get the best results since effective efficiency is at its peak for flow rates between 0.75 and 1.5 kg/s-m2, according to Experimental research has been done on the effects of heat transfer and friction qualities on air passing through a rectangular duct with V-down perforated baffles to create the roughness. In the experiment, the open area ratio ranged from 12% to 44%, the relative roughness pitch (P/e) ranged from 1-4, and the relative roughness height (e/H) ranged from 0.285 to 0.6. Nusselt number (Nu) and friction factor (f) are affected by roughness factors, and for ducts with a roughened test plate, an increase in heat transmission and friction loss has been observed. For flow and geometrical parameters with relative roughness pitches between 1.5 and 3, maximum Nusselt numbers are observed.

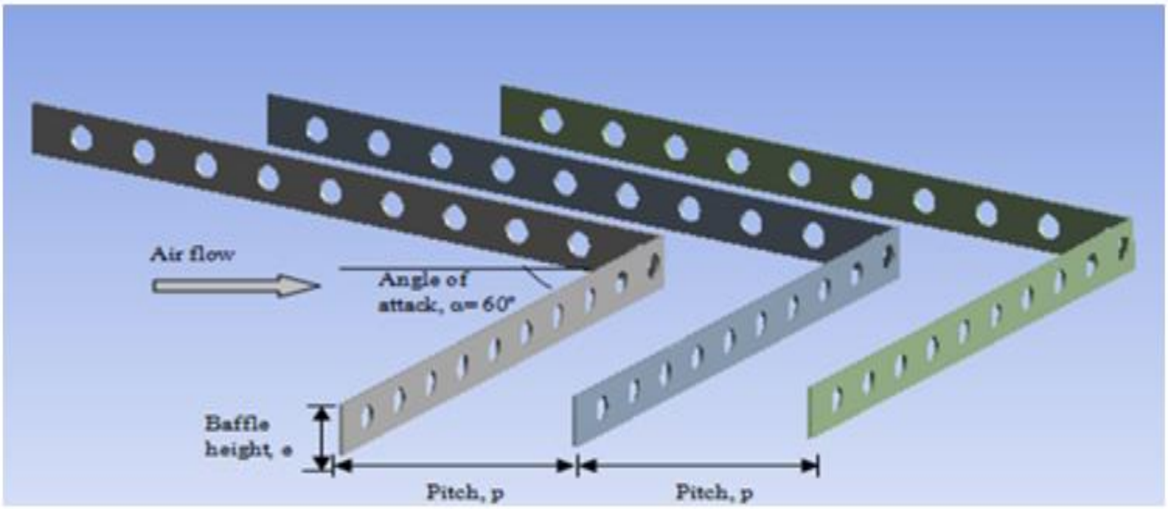

Fig. 11: Perforated V-Baffles by Chamoli et.al [13]

I. *Inclined and transverse ribs:*

In an experimental study by Varun et al. (2008) [14] to determine the thermal system efficiency of a solar-powered air heating system, ribs that are both inclined and transverse were used as textural components on the absorbent panel. The study found that a pitch relative roughness (P/e) of 8 produced the highest thermal efficiency.

Based on the experimental research conducted by many researchers, Table 4 also includes the produced correlations for the Nusselt number and friction factor within the range of operating conditions.

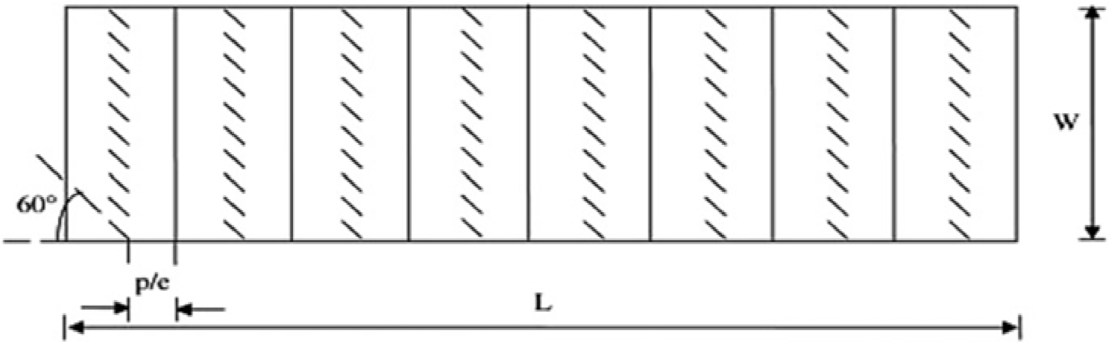

Fig. 12: Inclined and transverse ribs by Varun et.al [14]

Table 4: Heat transmission and friction factor correlations for various roughness geometries utilised in solar air heater duct

Researchers	Rib Geometry	Correlations Developed
Varun et.al[14]	Inclined and Transverse Ribs	$Nu = 0.00060 \left(\frac{p}{e}\right)^{0.0104} Re^{1.213}$ $f = \left(\frac{p}{e}\right)^{0.0114} Re^{-0.3685}$
Lanjewar et.al[9]	W-shape ribs	$Re = \sqrt{\frac{2}{f}} + 2.5 \ln\left(\frac{2e}{Dh}\right) + 3.75$ $e^{+} = \sqrt{\frac{f}{2}}\, Re\left(\frac{e}{Dh}\right)$ $g = \left[\left(\frac{f}{2St}\right) - 1\right]\sqrt{\frac{2}{f}} + R$
Saini and Saini[8]	Arc Shape ribs	$Nu = 0.00104\, Re^{1.3186}(e/D)^{0.3772}$ $(\alpha/90)^{-0.1198}$ $f = 0.14408 Re^{-0.17103}(e/D)^{0.1765}$ $(\alpha/90)^{0.1185}$
Jaruker,Saini,Gandhi [11]	Rib-Grooved	$Nu = 0.002062 Re^{0.936}(e/D)^{0.349}(p/e)^{3.318}$ $\times\, exp[-0.868\{ln(p/e)\}^{2}]\ (g/p)^{1.108}$ $\times\, exp[2.486\{ln(g/p)\}^{2} + 1.406\{ln(g/p)\}^{3}]$ $f = 0.001227(Re)^{-0.199}(e/D)^{0.585}(p/e)^{7.19}$ $(g/p)^{0.645} \times exp(-1.854\{ ln(p/e)\}^{2})$ $\times\, exp(1.513\{ln(g/p)\}^{2} + 0.8662\{ln(g/p)\}^{3})$
Saini and verma[12]	Rib dimpled ribs	$Nu = 5.2 \times 10^{-4} Re^{1,272}(e/D)^{0.033}(p/e)^{3.15} \times exp[-2.21\{ln(p/e)\}^{2}$ $\times\, exp[-1.30\{ln(e/D)\}^{2}]$ $fr = 0.0642 Re^{-0.423}(e/D)^{-0.0214}(p/e)^{-0.465} \times exp[0.054\{ln(p/e)\}^{2}$ $\times\, exp[0.840\{ln(e/D)\}^{2}\ ]$
Prasad and saini[5]	Small diameter protrusion wire	$fr = 2/[0.95(p/e)^{0.53} + 2.5 ln(D/2e) - 3.75]^{2}$
Aharwal et al.[10]	Inclined with gap ribs	$Nu = 0.00060 \left(\frac{P}{e}\right)^{0.0104} Re^{1.213}$ $f = 1.0858 \left(\frac{P}{e}\right)^{0.0114} Re^{0.3685}$
Chamoli and Thakur[13]	Perforated V-baffles	$Nu = 0.0296\, Re^{0.7848}(P/e)^{0.3007}(H/e)^{-0.6774}\ (\beta)^{-0.3571}$ $exp(-0.2548[(\text{In}(P/e)]^{2}) \times exp(-0.4406[(\text{In}(H/e)]^{2})$ $exp(-0.0863[(\text{In}(\beta)]^{2})$ $f = 0.632 Re^{-0.18}\left(\frac{P}{e}\right)^{-0.16}\left(\frac{H}{e}\right)^{1.05}(\beta)^{-0.13}$

IV. CONCLUSION

The following studies, which are reviewed in this paper, were carried out by various researchers to enhance heat transfer:

- Small diameter protrusion wires on the collection plates can be employed to increase the frictional value and thermal transfer efficiency of solar-powered air heating systems.
- In compared to a rectangular conduit that is smoother, the addition of 90º transverse ribs as roughness components on an absorber plate could improve the thermal transmission coefficient by 1.25–1.4 times under identical operating conditions and at higher Reynolds numbers.
- It has been found that the heat transfer coefficient is significantly increased when arc-shape parallel wire geometry is added to the solar air duct as artificial roughness. The largest Nusselt number enhancement was determined to be 3.80 times with a relative arc angle (/90) of 0.3333 and a relative roughness height of 0.0422. But only 1.75 times has the friction factor increased in response to these settings.
- W-down ribs are more effective than W-up and V-ribs throughout the parameter range evaluated, but W-up ribs, which have the maximum thermo-hydraulic performance of 1.81, are less effective.
- The inclined rib arrangement with a gap improves heat conduction and reduces friction in the roughened ducts. For the range of Reynolds numbers from 3000 to 18,000, the increase in Nusselt number and friction factor is in the range of 1.48-2.59 and 2.26-2.9 times of the smooth duct, respectively.
- The most efficient thermo hydraulic construction is one with rib-grooves, which can also be employed to maximize heat transfer.
- For dimple shaped ribsthe highest recorded Nusselt number is equal to a relative roughness height (e/D) of 0.0379 and a relative pitch (p/e) of 10. While relative roughness height (e/D) of 0.0289 and relative pitch (p/e) of 10 have been shown to correspond to the lowest value of friction factor, respectively.
- The baffled duct solar air heater has a thermal efficiency that is 20–80% higher than the smooth duct solar air heater. When flow rates are low, the augmentation is greater.
- The thermal effectiveness of the combined inclined and transverse surfaces is created at a relative roughness pitch of 8, which is dependent on the roughness factors in a modified solar-powered air heater.

V. NOMENCLATURE

Ap	Absorber plate area, $m2$
D	Conduit hydraulic diameter, m
e	height of ribs, m
e/D	Height relative roughness
fs	The smoother conduit frictional factor
f	The roughened conduit frictional coefficient
Gd	Distance of gap, m
G_d/L_v	Relative distance of gap
g	Width of gap, m
g/e	Relative gap width
H	Depth of the duct, m
l_v	A single v-shaped rib's length, m
Nu	Roughened duct Nusselt value
Nus	Smoother duct Nusselt value
P	Rib pitch, m
P/e	Pitch relative roughness
V	Air velocity, m/s
W	Duct Width, m
w	Width of a single v-shaped rib, m
W/w	Proportion of the width of the roughness
Re	Reynolds value
R (e +)	Reynolds roughness value

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