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Effect of Roughness Parameters in Solar Air Heater Duct: A Review

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Abstract:- Using both active and static technical categories, the transmission of heat can be improved. When compared to passive methods, which increase turbulent conditions by adding artificial protrusions in to the absorbent plate, active approaches show less promise. This article evaluates the many passive heat transfer techniques that can improve the air's convection heat transfer coefficient. In this study, we examine the impacts of artificial texture on the thermal characteristics of solar heating ducts for low-pressure drops. The work's primary focus is the mathematical and experimental exploration of heat conduction in the solar system's framework channels, without and alongside artificial protrusions. Additionally, different duct designs for solar thermal water heaters were investigated for both scientific and experimental uses in a range.

Keywords:- *Artificial texture, heat exchange, passive and active technologies, solar-powered air heater, and coefficient of friction.*

I. INTRODUCTION

There are many different types of energy, which is crucial for the expansion and industrialization of the world economy [1, 2]. Currently, traditional energy sources such as natural gas, coal, and petroleum are responsible for meeting the majority of the world's energy demands. The bulk of the world's energy demands are able to be met by fossil fuels, but they have a number of disadvantages, such as (a)limited resources[3,4], ownership by a small number of countries[3,4], variable prices[3,4], environmental issues[3,5], and a lack of international energy security[3,5]. Solar energy and other renewable energy sources must be used to solve the energy dilemma [6]. Through a variety of technologies, including photovoltaic panel's energy, thermal energy from the sun, concentrated solar power, and passive and active energy, it is possible to harness the abundant and readily available solar energy. Solar air heating systems, which are affordable and simple to use.

Seven parts make up a conventional solar air heating system: a supply duct, an exit duct, an absorbing tray, glass, a stiff frame, insulation, and a solid block of wood. On the upper surface, a glazing arrangement is offered to absorb additional solar radiation. The sun energy that reaches the glazing is captured by the highly thermally conductive solar absorber plate, which controls how efficiently heat is transferred to the heated air. Acrylic, tempered glass, polycarbonate, and other glazing materials are frequently used [8]. The absorber plate's performance will depend on how it is built and made of what materials and a specific alloy of aluminium is frequently chosen because of its low weight, high strength, and simplicity of manufacture [9].

Solar air heaters have advantages over other solar thermal technologies as they do not have problems with air leakage, corrosion, or freezing and do not require low-tech equipment for maintenance and repair [7].

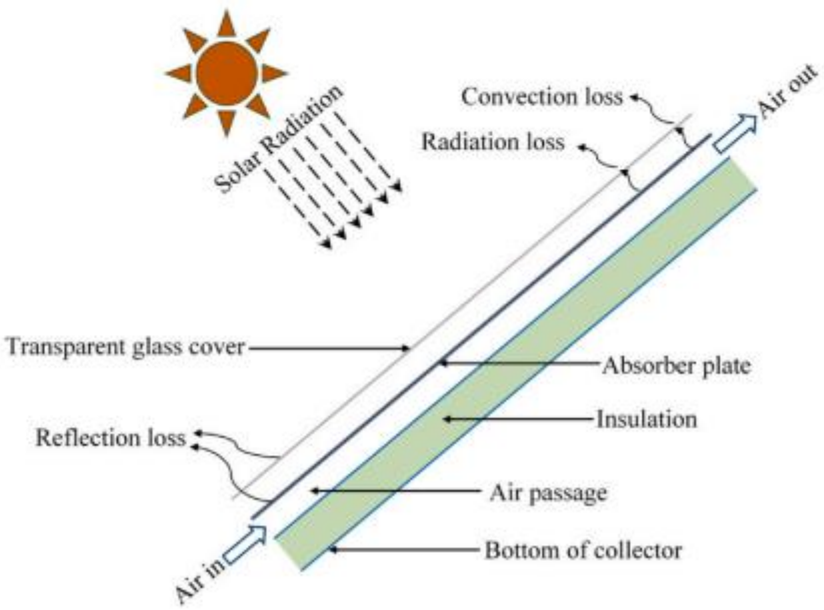

Fig. 1: Solar Air Heater by Mahanand et.al [19]

II. CONCEPT OF ARTIFICIAL ROUGHNESS

Artificial irregularity is surface roughness that has been purposefully added to a substance to enhance heat transmission. The conduit walls or absorbent plates of a solar-powered air heater can be made rougher to achieve this which can increase the air flow turbulence inside the heater. Artificial texture has been shown to significantly boost the solar air heaters' transfer of heat rate, resulting in higher thermal efficiency and lower running costs. The roughness elements' enhanced turbulence can intensify air mixing and thin the boundary layer, which in turn raises the value of the coefficient of heat transmission.

Solar-powered air heaters can use a variety of roughness components, including ribs, grooves, dimples, and protrusions. The ideal design and arrangement of these elements will depend on the specific conditions and intended usage of the solar-powered air heater. Overall, artificial texture represents a promising technique to improve heat transmission in solar-powered air heaters, thereby boosting their overall effectiveness and economic viability.

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

A. Pitch relative roughness(p/e):

The pitch relative roughness is a feature that describes the geometry of artificial texture elements in a channel or duct. It is a dimensionless number which indicates the proportion of the roughness component height to pitch in relation to that the duct hydraulic diameter. In other words, it is the proportion of the rib's height to the distance between its neighboring ribs. Researchers have looked into how pitch relative roughness affects flow patterns and heat transfer coefficients, and table 1 lists the value of relative roughness pitch for several artificial geometries.

Table 1: lists the relative roughness pitch values for several artificial roughness geometries that result in the highest heat transmission coefficients.

Investigators	**relative roughness pitch value at which the heat transmission coefficient is at its highest** (P/e)	**Roughness geometry**
Prasad and Saini [11] (1988)	10	Wire
Sahu and Bhagoria [13] (2005)	13.33	90°broken transverse
Jaurker et al. [14] (2006)	6	Transverse rib-grooved
Varun et. al[15] (2008)	8	Combination of inclined and transverse ribs
Lanjewar et.al[16] (2011)	10	W-shape Ribs
Sethi et.al[17] (2012)	10	Dimple shaped Elements
Kumar et.al[18] (2013)	8	Multiple V-shapes with Gap ribs
Mahanand et.al[19] (2020)	7.14	Inverted T-shape ribs
Kumar et al.[20] (2017)	8	S Shaped ribs
Hans et al.[21] (2017)	10	Broken Arc Shape ribs

The flow patterns below a rib are affected by its corresponding roughness pitch, evidently in Figure 2 from Prasad et al. [11]. The unattached shear layer separates at the rib and does not reconnect when the corresponding pitch relative roughness (p/e) is lowest between 8 and 10. Near reconnecting point, the thermal transfer coefficient has become highest. Reattachment does not take place, which lowers the thermal intensification rate, if the pitch relative roughness (p/e) is smaller than 8 to 10. As the pitch drops, frictional factor rises. In contrast, the transfer of heat is improved when the pitch relative roughness (p/e) ratio is raised over 10.

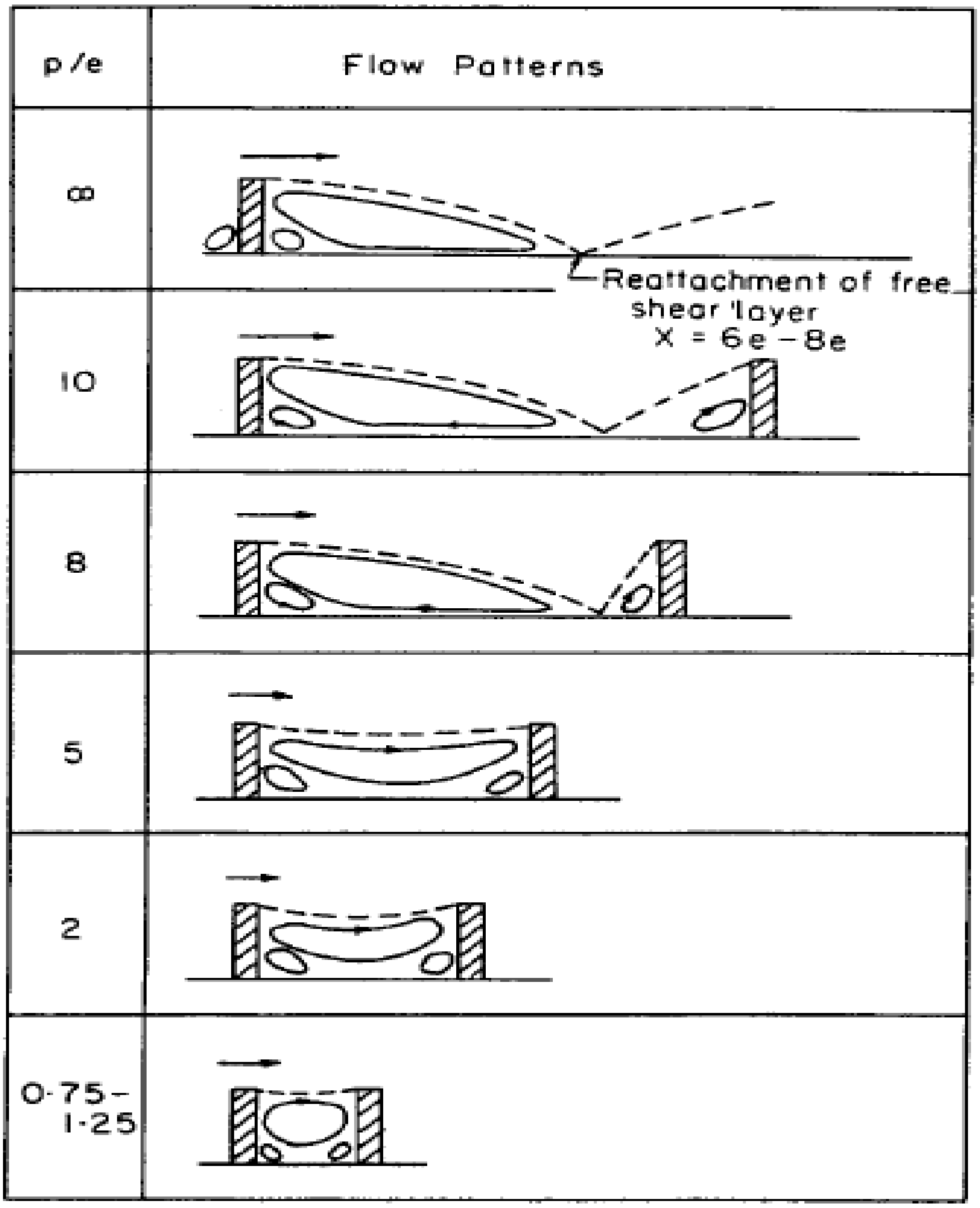

Fig. 2: Depicts the patterns of ribs flowing downward while based on the level of texture as a measure of Pitch relative roughness by Prasad and Saini (1988) [11]

B. Height-relative roughness(e/D)*:*

Engineers employ a dimensionless metric called the height relative roughness to describe the geometry of the components with a rough surface in a conduit or channel. The proportion of the height of the roughness elements to the conduit hydraulic diameter, indicated as (e/D), where e is the height of the roughness components and D is the conduit hydraulic diameter, is used to represent the height relative roughness.

When designing roughness components, the relative roughness height is an important metric to consider achieving acceptable levels of turbulence and heating transfer enhancement while minimizing pressure drop and energy consumption. Figures 3a and 3b (Prasad & Saini, 1991) specifically show how adjusting the rib height affects the rib's uniform sub-layer and its downstream component, respectively. Repetitive ribs that split the viscous sub-layer speed up heat transmission causing a localized wall disturbance. The rate of transference of heat would increase if the ribs extended past a viscous sub-layer, but friction losses would also rise. The roughness height should be somewhat the optimal thermo-hydraulic performance factors, more than the thickness of the sub-layer of transitioning (Prasad & Saini, 1991). The numerical data of height relative roughness (e/D) for the highest heat transmission coefficient are shown in Table 2.

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Table 2: for different texture shapes used in the solar air heater duct height relative roughness (e/D) values shown

Investigators	**Maximum thermal transmission coefficient number at a given height relative roughness (e/D)**	**Roughness geometry**
Prasad and Saini [11] (1988)	0.033	Wire
Sahu and Bhagoria [13] (2005)	e=1.5mm	90°broken transverse
Jaurker et al. [14] (2006)	0.036	Transverse rib-grooved
Varun et. al[15] (2008)	0.030	Combination of inclined and transverse ribs
Lanjewar et.al[16] (2011)	0.03375	W-shape Ribs
Sethi et.al[17] (2012)	0.036	Dimple shaped Elements
Kumar et.al[18] (2013)	0.043	Multiple V-shapes with Gap ribs
Mahanand et.al[19] (2020)	0.042	Inverted T-shape ribs
Kumar et al.[20] (2017)	0.043	S Shaped ribs
Hans et al.[21] (2017)	0.043	Broken Arc Shape ribs

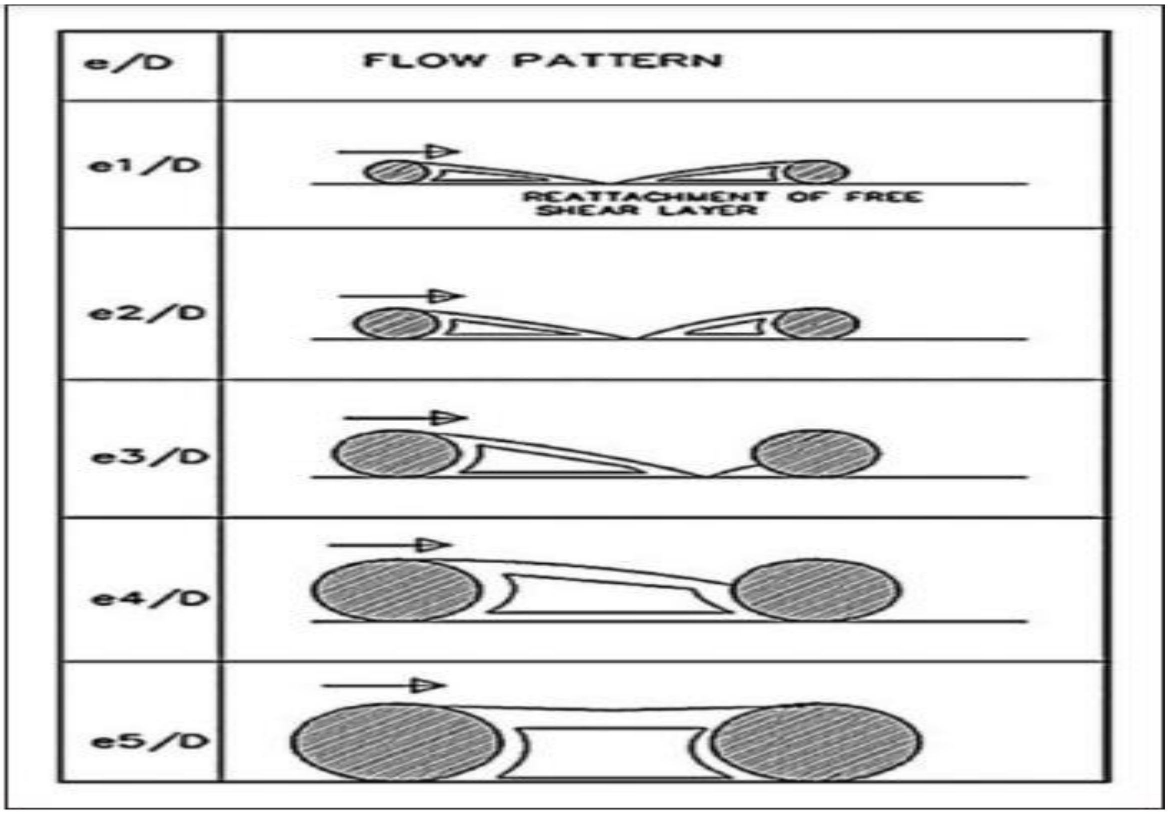

Fig. 3(a): Displays the patterns of flow beneath the wires and roughness as an indicator of corresponding roughness height by Prasad & Saini (1988) [11]

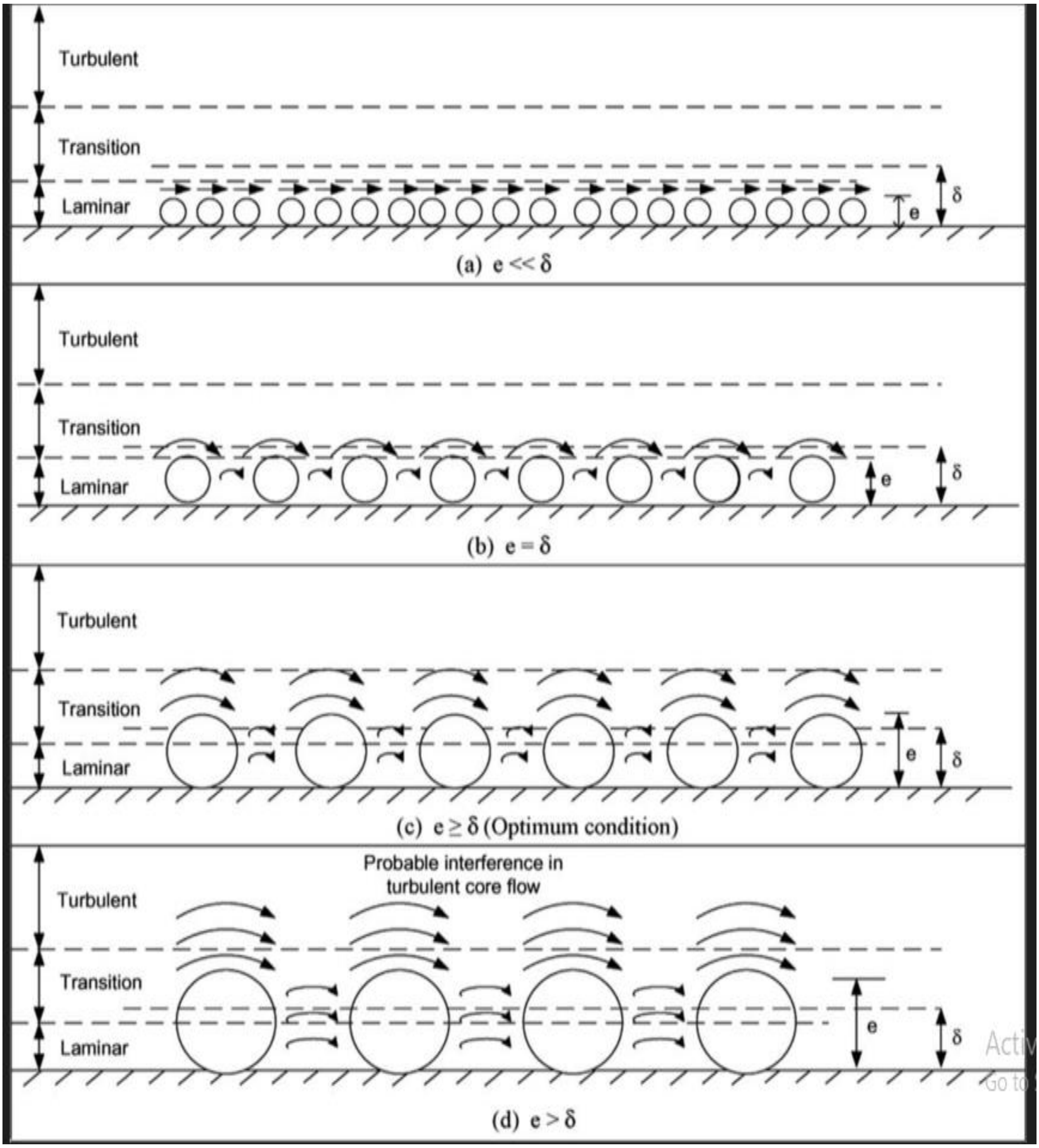

Fig. 3(b): shows the roughness height in relation to the a laminar sub layer by Prasad & Saini (1991) [12]

C. Angle of attack:

When describing the affect of artificial texture on solar-powered air heaters, the angle of attack is used to describe the direction of fluid flow as it comes into contact with roughness elements on the surface. This direction can affect the duct's turbulence and enhanced heat transfer. The roughness elements are often positioned at specific angles with regard to the flow direction depending on the system design. The angle of attack can have an impact on the amount of disturbance and mixing in the fluid flows, and therefore on the system's decrease in pressure and thermal transfer coefficient. According to research done to examine the impact of rib alignment, the angle has the most influence on the pattern. Due to the additional flow that is created by the inclined ribs, which also breaks up the viscosity sub-layer and creates localized wall turbulent conditions, heat can be transferred more quickly than through transverse ribs. The angle of attack values (α) for the largest thermal transfer coefficient for various artificial roughness types are shown in Table 3.

Table 3: Angle of approach (α) for the highest heat transmission coefficient value for various roughness kinds of elements

Investigators	Range of Value of (α) for maximum heat transfer coefficient	Roughness Geometry
Prasad and Saini [11] (1988)	-	Wire
Sahu and Bhagoria [13] (2005)	90º	90°broken transverse
Jaurker et al. [14] (2006)	-	Transverse rib-grooved
Varun et. al[15] (2008)	60º	Combination of inclined and transverse ribs
Lanjewar et.al[16] (2011)	30º-75º	W-shape Ribs
Sethi et.al[17] (2012)	45º-75º	Dimple shaped Elements
Kumar et.al[18] (2013)	30º-75º	Multiple V-shapes with Gap ribs
Mahanand et.al[19] (2020)	-	Inverted T-shape ribs
Kumar et al.[20] (2017)	30º-70º	S Shaped ribs
Hans et al.[21] (2017)	15º-75º	Broken Arc Shape ribs

III. SHAPE OF ROUGHNESS ELEMENTS

The artificially roughed elements used in solar-powered air heaters can take a number of shapes according to the arrangement and operational conditions. But their main method of operation is to stir up the fluid flow, which accelerates heat transmission and improves thermal effectiveness. The form and the way the roughness features aligned can have a considerable impact over the stream properties, radiation transfer, and pressure reduction in the system. To get the best possible thermal performance and efficiency, the shape and orientation of the roughness components must be carefully chosen.

The following studies examined how the Reynolds number and Nusselt number are impacted by the design of roughness elements used to create artificial surface abrasion to improve the air heating system driven by solar energy's heat transmission:

A. Small diameter protrusion wires:

Prasad et al. (1988) [11] carried out an experiment to ascertain how a fully formed turbulence's thermal transfer coefficient and friction value are impacted by the height relative roughness (e/D) and pitch relative roughness (p/e) in a duct air warmer driven by solar energy. Figure 4 depicts the tiny diameter protrusion wires for the conduit from the absorbent plate. For height relative roughness of 0.020, 0.027, and 0.033, it was recognized that an average Nusselt number in the conduit that is rough was 2.10, 2.24, 2.38 and 3.08, 3.67, 4.25 times greater than in the smoother conduit. The average Nusselt value and frictional value enhanced by about 2.38, 2.14, 2.01, and 4.25, 3.39, 2.93 times, respectively, in the duct's rough surface compared to the smoother duct. At pitch relative roughness of 10, 15, and 20, the corresponding values are 2.38 and 4.25, which are numerous times that of a smoother duct. These were the biggest improvements in the thermal coefficient of transmission and the value of friction.

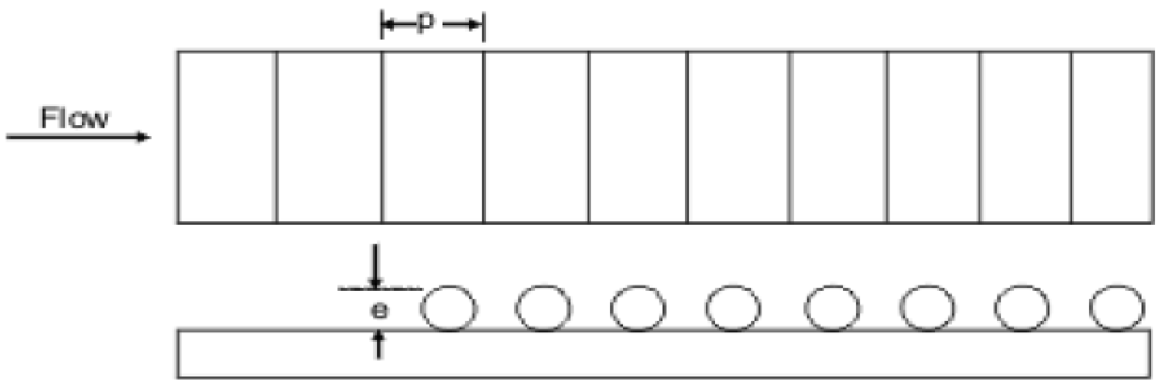

Fig. 4: The form and direction of the texture element that is analyzed by Prasad and Saini (1988) [11]

B. 90° broken transverse ribs:

The impact of rib pitch on the thermal transference rate and frictional value Studied by Sahu and Bhagoria in 2005 [13] evaluated values for 90° divided transversal ribs with a rib depth of 1.5 mm and an aspect ratio of 8. The results are depicted in Figure 5.As the pitch was changed from 10 to 30, not just the uppermost portion of the rib, but also the margins at the extremities of the ribs, experienced division, creating an auxiliary stream that stopped the boundary layer's growth downstream of the adjacent connection zone. At a pitch roughness p of 20 mm, the highest Nusselt value was reached; as roughness pitch increased, it decreased. Based on their test results, the investigators found that, the textured solar power air heater's efficiency varies based on the flow circumstances. Highest level of thermal effectiveness ranged from 51% to 83.5%. The best thermal effectiveness of 83.5% was reached using a 20 mm pitch.

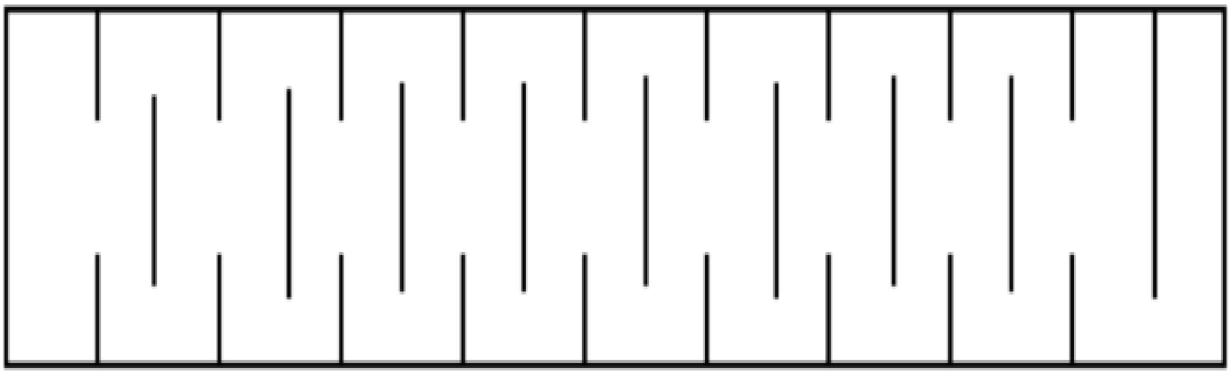

Fig. 5: Displays broken transverse ribs by Sahu and Bhagoria in 2005 [13]

C. Transverse rib-grooved:

Figure 6 depicts the results of a research by Jaurker et al. (2006) [14] to determine the effects of the pitch relative roughness, height relative roughness, and related groove alignment on the coefficient of transmission and friction value of rib-grooved artificial roughness. According to the investigation, the transmission of heat increased to its optimum at a pitch relative roughness of about 6 and on either end of this pitch, reduced. When compared to a smooth duct, a groove alignment to pitch ratio of 0.4 was found to be the ideal situation for heat transfer. Within the parameters studied, the addition of rib-grooved artificially roughened the frictional value had been raised by 3.6 times whereas the Nusselt value was increased by 2.7 times.

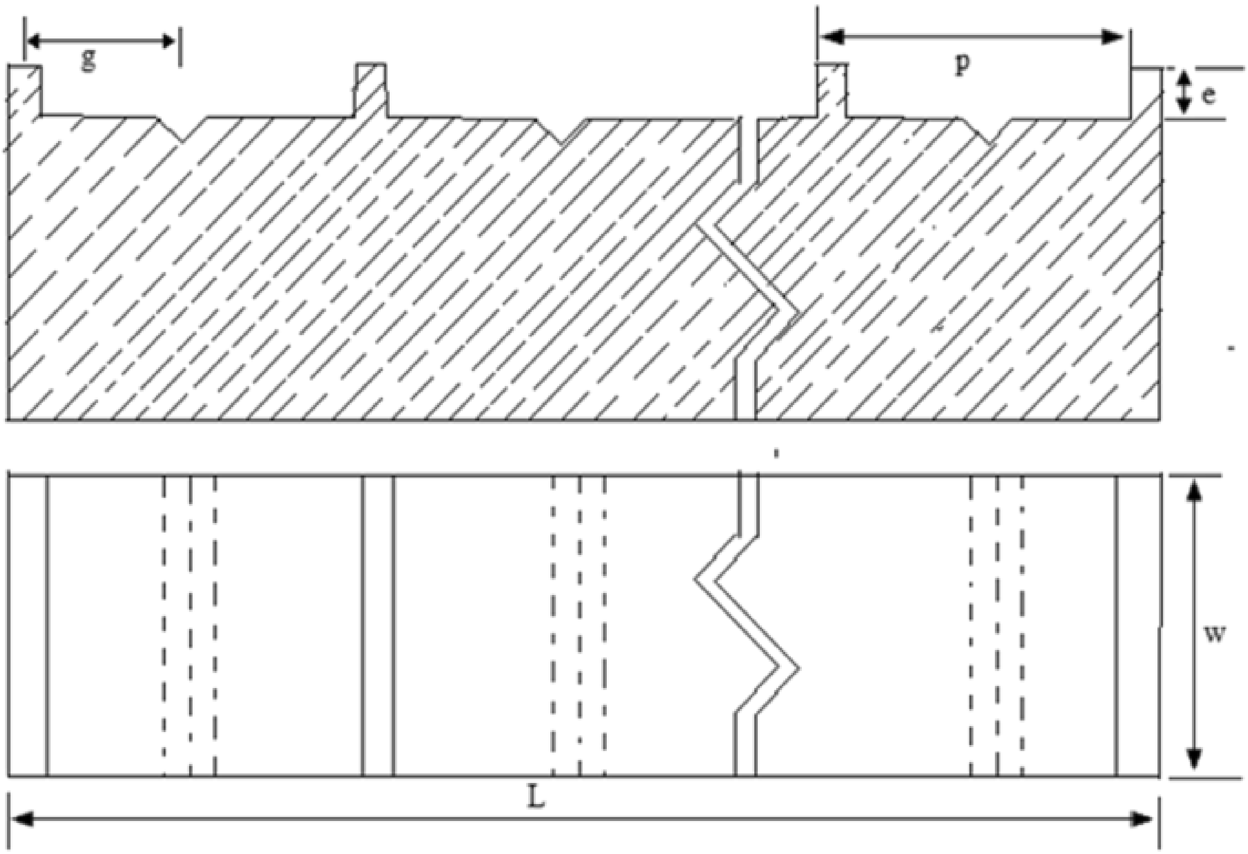

Fig. 6: Surface roughness component type and position studied by Jaurker et al. (2006) [14]

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D. Combination of inclined and transverse ribs:

Figure 7 demonstrates how ribs that is both inclined and transverse were used as texture components on the absorbent panel in Varun et al.'s (2008) [15] experimental research of a solar-powered air heating system's thermal system efficiency. According to the investigation, the most effective thermal efficiency was achieved with a pitch relative roughness (P/e) of 8.

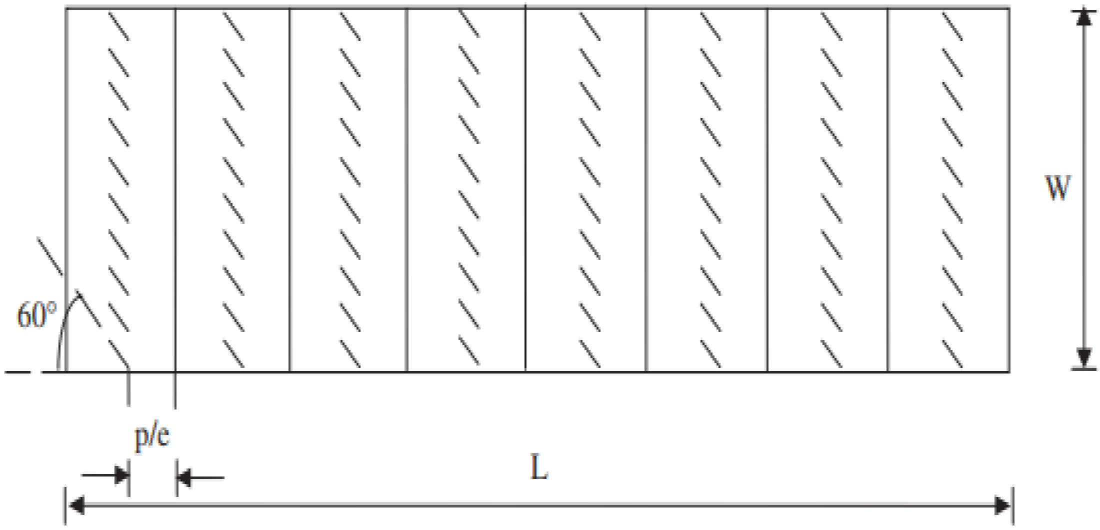

Fig. 7: Absorber plate illustrating the roughness feature according to Varun et al. [15]

E. W-shape Ribs:

Figure 8 depicts the W-shaped rib artificial roughness element that was used in an experiment by Lanjewar et al. (2011) [16] for a homogeneous heat flux in a turbulent flow. The working fluid used was air, and the friction and transfer of heat coefficient were calculated experimentally for a Reynolds value range of 2300–14,000. It was determined that the Nusselt value increases and the frictional value decreases as the Reynolds value increased. Additionally, it was discovered that W-down ribs performed more efficiently in terms of thermo-hydraulics than W-up and V-ribs. The greatest thermo-hydraulic efficiency for W-down ribs was found to be 1.98 over the range of the parameters evaluated, whereas it was 1.81 for W-up ribs.

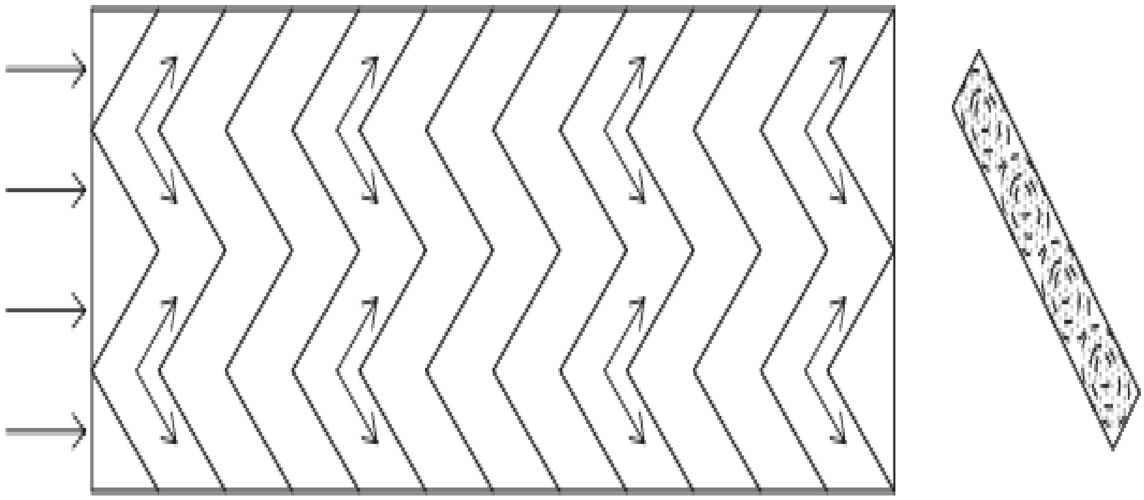

Fig. 8: Structure of W-shaped texture by Lanjewar et al. [16]

F. Dimple shaped Elements:

In order to better understand the dimple-shaped texture put in an angular pattern on an absorbent plate, which affects the thermal and fluid transfer properties of a solar-powered air heater, as shown in Figures 9a and 9b, Sethi et al. (2012) [17] conducted an experiment. According to the study, when the Reynolds value increased, the Nusselt value also increased while the frictional value decreases. The roughened duct had a greater Nusselt value and frictional factor than the duct that was smoother. With a height relative roughness of 0.036, a pitch relative roughness of 10, and an arc angle of 60º, the maximum Nusselt value was achieved.

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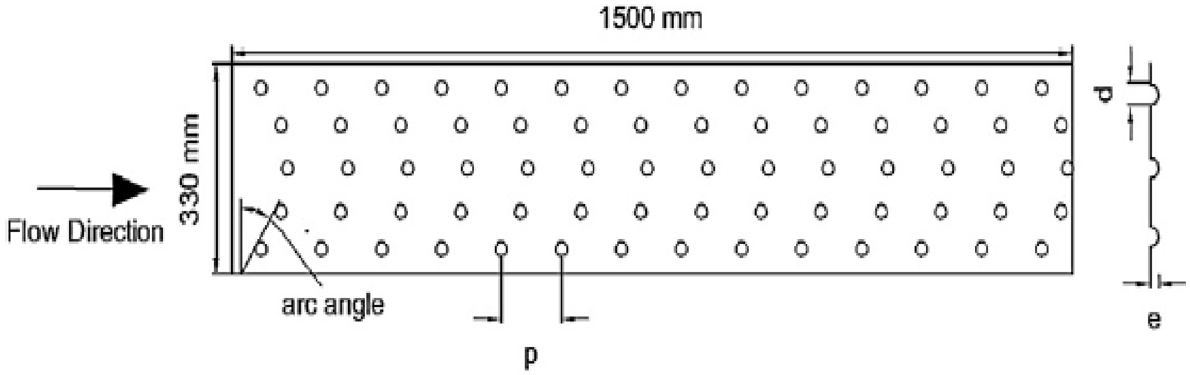

Fig. 9(a): W-shaped textured absorbent plate diagram by Sethi et al.'s [17]

Fig. 9(b): W-shaped textured absorbent plate depicted by Sethi et al. [17]
Fig. 9: (a) The absorbent plate's diagram. (b) A visual representation of the absorber plate

G. Multiple V-shapes with Gap ribs:

Using a multi-v shaped rib with a gap to purposefully create an artificial texture, Kumar et al. (2013) [18] investigated the effects of the artificial texture on the coefficient of heat transmission and the frictional factor roughen one major wall of a solar-powered air heater duct. As they affected the thermal transmission coefficient and frictional factor, the height relative roughness(e/D), width of relative roughness(W/w), relative gap distance (G_d/L_V), relative gap width (g/e), angle of attack (α), and pitch relative roughness (P/e) were all assessed in the study. When compared to a smooth duct, the number of V-shaped ribs with gaps produced Nusselt value that were up to 6.74 times higher and the frictional value that were up to 6.37 times higher. For the height relative roughness of 0.043 the relative gap distance of 0.69 and relative gap width of 1.0, angle of attack of 60º, and relative roughness width of 6.0, and relative roughness pitch of 8.0 resulted in the biggest improvement in Nusselt value. The results showed how efficiently adding artificial roughness with gaps in several V-shaped ribs can improve heat transmission in solar powered air heaters.

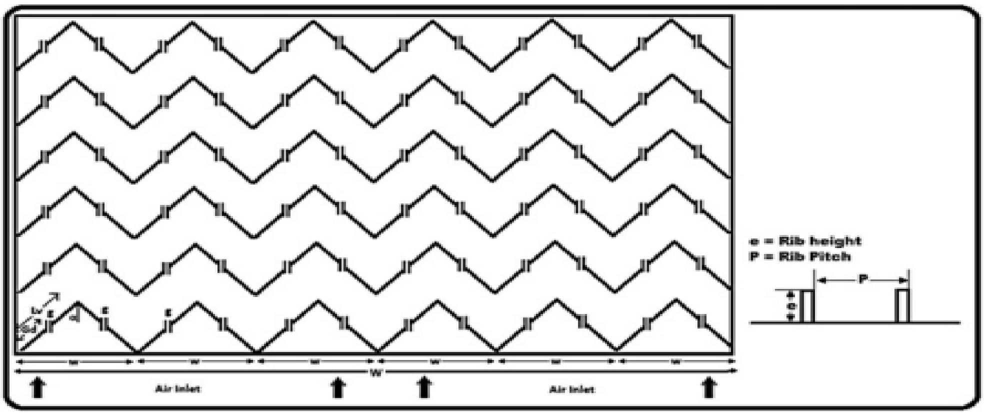

Fig. 10: Multiple v-shaped ribs having a gap by Kumar et al. [18]

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H. Inverted T-shape ribs:

A computational analysis of the conduit of a solar-powered air heater field of flow and thermal transmission characteristics with transverse inverted-T shaped ribs was done by Mahanand et al in 2020 [19]. The study used a two-dimensional RNG-k-model to examine a number of variables, including (p/e) values between 7.14 and 17.86 and Reynolds numbers between 3800 and 18000. The simulation was run under conditions with an average solar radiation intensity of 1000 $(w/m^2)$of heat flux. Figure 11 illustrates the findings, which revealed that the solar air heater obtained a thermal increase factor of 1.87.

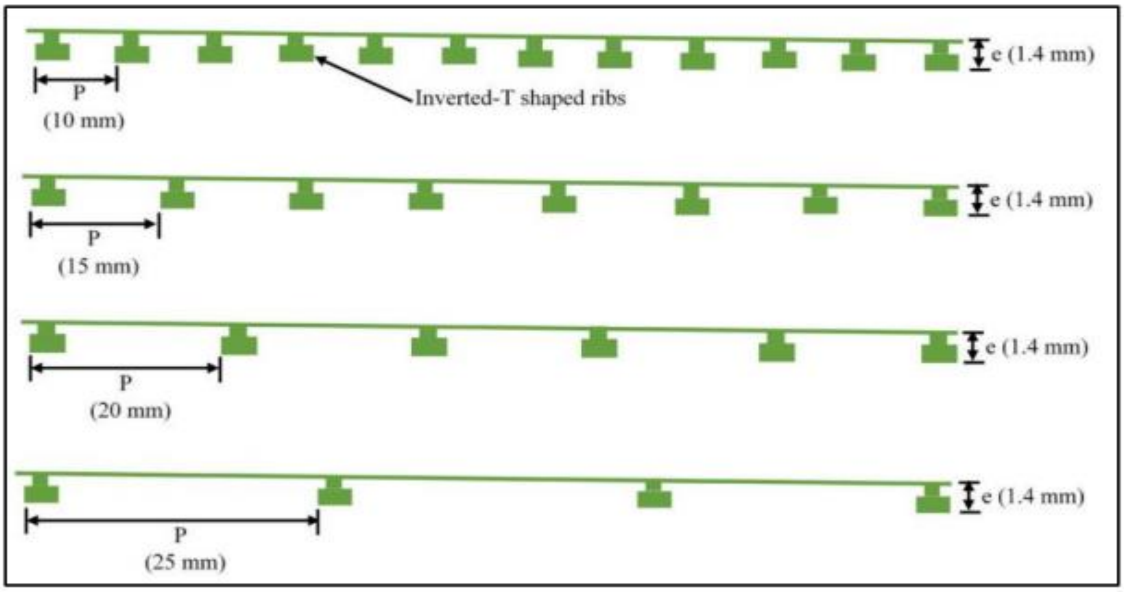

Fig. 11: Inverted-T structured ribs by Mahanand et al. [19]

I. S Shaped ribs:

Kumar et al. (2017) [20] performed a study using experiments to look at the characteristics of heat transmission and frictional factor of S-shaped roughness texturing on a solar-powered air heater duct's absorbent plate, illustrated in Figure 12. The study focused on how various roughness parameters, such as the height relative roughness (e/D) ranging from 0.022 to 0.054, pitch relative roughness (P/e) ranging from 4 to 16, Reynolds value (Re) ranging from 2400 to 20,000, and arc angle (α) ranging from 30º to 75º, affected heat transmission and frictional value. The greatest Nusselt value and frictional value were obtained for the arc angle of 60º, height relative roughness of 0.043, and relative roughness width of 3 and pitch relative roughness of 8.

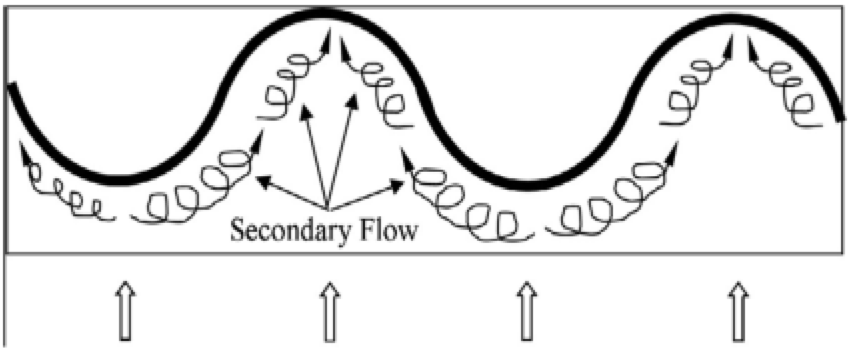

Fig. 12: S shaped ribs by Kumar et. al [20]

J. Broken Arc Shape ribs:

The results of a research study by Hans et al. [21] investigating the effects of broken arc roughness geometry on the transmission of heat and friction value of a SAH duct are presented in Figure 13. The study considered a range of parameters, including pitch relative roughness (P/e) between 4 and 12, arc angle (α) between 15° and 75°, relative gap width (g/e) between 0.5 and 2.5, and relative gap position (d/w) between 0.20 and 0.80. The relative roughness height (e/D) ranged from 0.022 to 0.043, and the Reynolds value (Re) ranged from 2000 to 16,000.

The study found that the broken arc rib roughened duct outperformed the duct which is smooth in terms of Nusselt value and factor of friction by a maximum margin for the parameter range under consideration. Within this parameter range, the broken arc rib roughened duct showed a maximum improvement in Nusselt value and frictional factor of 2.63 and 2.44 times, respectively. Additionally, continuous arc rib roughened duct improvements were 1.19 and 1.14 times greater than each other.

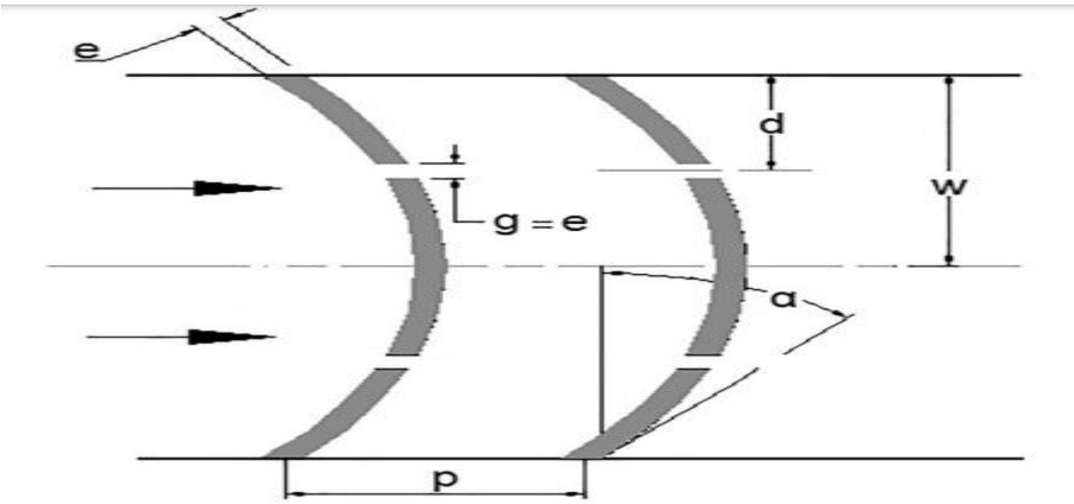

Fig. 13: "Broken arc" ribs by Hans et al. [21]

IV. CONCLUSION

In order to improve heat transfer, several researchers have conducted the following research, which is reviewed in this paper:

- Small diameter protrusion wires on the collection plates can be used for improving the thermal transfer efficiency and frictional value of air heating systems powered by the sun.
- Under identical conditions of operation and at higher Reynolds numbers, the addition of 900 transverse ribs as roughness components on an absorber plates could increase the thermal transmission coefficient by 1.25–1.4 times in comparison to a rectangular conduit that is smoother.
- The rib-grooved structure, which can also be used to optimize heat transport, offers the most effective thermo-hydraulic effectiveness.
- In a modified solar-powered air heater, which depends on the roughness factors, the thermal efficiency of the combined inclined and transverse the greatest thermal effectiveness is produced at a pitch relative roughness of 8.
- Within the parameter range tested, W-down ribs are more efficient than W-up and V-ribs, compared to W-up ribs, which have a highest thermo-hydraulic performance of 1.81.
- In contrast to flat surfaces, adding a dimple-type roughness feature to the absorber plate raises the Nusselt value and as the Reynolds value rises, reduces the frictional value.
- A multi-V-shaped rib with a gap increases the Nusselt value and frictional value up to 6.37 and 6.74 times, correspondingly, in contrast to a conduit that is smooth, with the multi-V-shaped with gap rib performing better.
- Within the range of Reynolds value, inverted-T ribs offer a higher Nusselt number for solar air heaters than semi-circular ribs. However, for Reynolds numbers greater than 12,000, Inverted-T ribbed SAH has a higher average Nusselt value than square ribbed SAH. For Reynolds numbers under 1200, Squared and quarter-circular ribs have fairly comparable Nusselt number values.
- The impact of the friction penalty is minimal if the flow disruption only impacts its laminar sub-layer.
- Compared to inclined and v-ribs with gaps, the broken arc rib has less heat transfer improvement, but for the Reynolds number, its thermal and hydraulic performance is superior in a range that is acceptable for solar air heaters.

➢ *Nomenclature:*

A_p	Absorber plate area, m^2
D	Conduit hydraulic diameter, m
e	height of ribs, m
e/D	Height relative roughness
f_s	The smoother conduit frictional factor
f	The roughened conduit frictional coefficient
G_d	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
Nu_s	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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