Heat Transfer Augmentation in Artificially Roughened Solar Air Heaters: A Review

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ABSTRACT

One of the most basic, affordable, and user-friendly pieces of equipment is the solar air heater, which finds extensive usage in process heating, space heating and agriculture. It uses a very basic method wherein an absorber plate absorbs solar heat and uses it to heat the air. However, because there is a laminar sub-layer between the absorber plate and the air flow, its thermal performance is poor. Low heat transfer rate is also thought to be caused by low air thermal conductivity, friction losses, and heat losses. To get over this restriction, creating artificial roughness is thought to be a useful method for increasing the airflow in the duct's rate of heat transfer. This approach was the subject of extensive research, which effectively broke the laminar sub-layer and decreased the heat resistance. Many varieties of roughness are investigated by different researchers, including rib roughness, protrusion roughness, wire fixation, wire mesh, chamfered ribs, wedged shaped ribs, protrusions etc. Enhancing the form, size, height and pitch of the roughness led to an increase in the rate of heat transmission. Numerous similar studies conducted by different writers and academicians are included in the current work as a review.

Keywords: *Solar air heater, laminar sub-layer, artificial roughness, heat transfer.*

I. INTRODUCTION

Different types of energy have become more and more vital to global industrialization and economic growth. The pace of energy consumption has increased due to both the growing global population and growing material demands. Since the earth's limited energy supplies are running out, the rapid growth in energy consumption that has marked the last 50–100 years cannot go indefinitely. On the other hand, life on Earth is threatened by environmental deterioration brought on by the use of fossil fuels. The development of renewable energy sources has gained momentum due to environmental risks and the world's decreasing fossil fuel supplies. Solar energy is the most promising long-term resource for supplying the steadily rising need for energy among a wide variety of options. Solar radiation, which is freely available, serves as an endless, non-polluting fuel source. Using solar collectors to transform solar energy into thermal energy is the most straightforward way to use it for heating purposes. Flat plate collectors are used in solar water heaters and solar air heaters, which are typically used to heat water and air, respectively. Compared to solar water heaters, solar air heaters are said to be smaller and simpler. They don't suffer from freezing or rust either. Compared to solar water heaters, solar air heaters are easier to operate and may be made with less expensive and less material. In general, solar air heaters are thought to be beneficial for tasks like seasoning wood, drying crops, and room heating. Due to its low material and cost requirements, solar air heaters have a significant position in solar thermal systems. Because of the limited rate of heat transfer capabilities between the absorber plate and the air flowing in the duct, solar air heaters are typically thought to have lower thermal efficiencies. The rate of heat transfer must be increased in order to increase thermal efficiency and make a solar air heater a more efficient solar energy utilization system. The present paper reports the approach of artificial roughness by various researchers to increase the thermal performance.

II. ARTIFICIAL ROUGHNESS INTERPRETATION

Nagyach et al. [1] described the artificially roughened solar air heater duct using rib geometries as shown in the Fig. 1. The roughness geometries employed in solar air heater are a helpful technique to improve heat transfer to fluid traveling over the channel, they reported maximum heat transfer compared to the plain surface. It was found that the arrangement and placement of the ribs on the absorber panel affect the different roughness geometry types used in solar air heater. **Karmveer et al. [2]** tried to investigate the thermal and friction properties of different man-made ribs in solar air heater ducts. This paper's literature assessment led to the conclusion that, in comparison to other roughness geometries, multi-V and multiarc-shaped roughnesses exhibit greater thermohydraulic performance. Fig. 2 shows the geometry of Chamfer transverse ribs. The multi-V-ribs' introduction of limb gaps greatly increased the amount of turbulence. The friction factor was larger in the case of the multi-V-shaped ribs and lower in the case of the arc-shaped circular dimples.

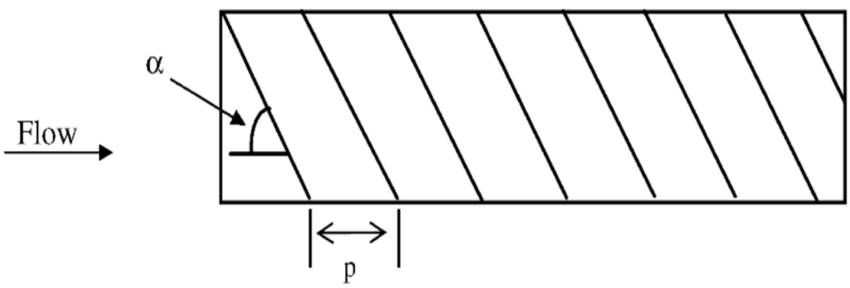

Fig. 1. Schematic of transverse inclined continuous ribs [1].

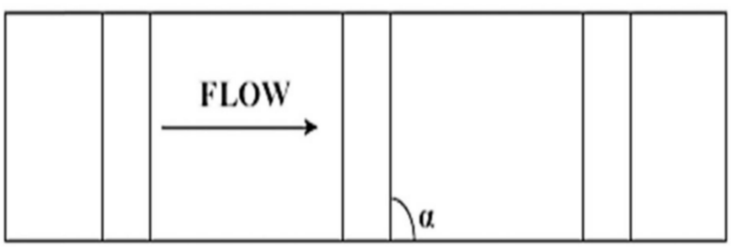

Fig. 2. Chamfered transverse rib roughness [2].

Bhushan and Singh [3] revisited the heat transmission and friction characteristics of solar air heater’s using distinct artificial roughness. The experimental tests conducted by different researchers and the methodology of creating artificial roughness was thoroughly discussed and documented. Fig. 3 shows the geometry of transverse broken ribs. Artificial roughness was found to be an effective way to increase the thermal efficiency of solar air heaters. Tables with correlations between the friction factor and the heat transfer coefficient were also discussed. **Patil et al. [4]** reviewed the best way to increase the rate of heat transfer from the heated surface to the flowing fluid at the expense of a slight increase in fluid friction is to use artificially roughened surfaces with various types of roughness geometries. The below Fig. 4 shows the arc shaped roughness. To improve thermal performance, many researchers mostly recommended roughness in the form of ribs, wire matrix, and dowels. In terms of thermal performance, rib roughness was determined to be the best performer among all. Many studies using computational, PIV, and other flow visualization techniques presented the mechanism of fluid turbulence and heat transfer in the case of various rib geometries; however, in order to choose the best fit roughness geometry in solar air heaters, a clear interpretation of secondary fluid flow and its effects on flow field had to be explored. One of the most well-liked types of roughness, multi V rib roughness, had lately been examined and has demonstrated unique performance in the case of solar air heaters. **Bisht et al. [5]** reviewed the heat transmission and friction properties of solar air heaters that were purposely roughened using various roughness geometries. In addition to discussing earlier advancements and shedding light on potential future possibilities, he provided an authoritative description of the topic's current state of progress. Using correlations suggested by the literature, an attempt was made to compare the performance of solar air heaters with various roughness geometries. To assess the performance of various roughness geometries, the thermo-hydraulic performance parameter (η), thermal efficiency (η), thermal efficiency improvement factor (TEIF), effective efficiency (η), and energetic efficiency (η) were measured.

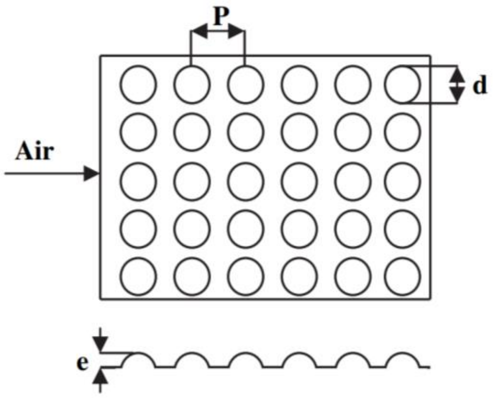

Fig. 3. Geometry of dimple shape absorber plate [3].

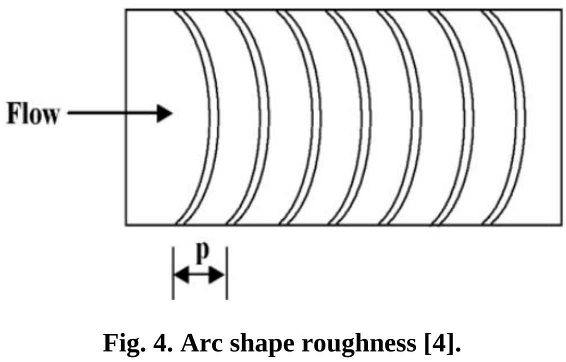

Fig. 4. Arc shape roughness [4].

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III. RIBS AS ARTIFICIAL ROUGHNESS

Singh et al. [6] looked at the novel idea of using rotating cylindrical ribs to create artificial roughness in solar air heaters in order to improve their thermo-hydraulic performance factor as shown in Fig. 5. For every rotational speed, friction factor values dropped as Reynolds numbers increased. It was possible to achieve the highest thermo-hydraulic performance factor of 1.89, which was 32% better than the best results for static ribs. For static cylindrical ribs aligned perpendicular to the absorber plate, at $R_e = 8000$, e = 3.5 mm, d = 3 mm, S = 20 mm, and P/e = 10, the greatest THPF value of 1.43 was attained. For every rotational speed, friction factor values fall as Reynolds numbers increased and converge at $R_e = 24000$. But for N = 10,000 RPM, the highest friction factor of 0.0267 reached at $R_e = 5000$. With rotational ribs, the maximum thermo-hydraulic performance factor of 1.89 was achieved at $R_e = 5000$, which is 32% higher than the greatest performance for static ribs. The rotational speed is 10,000 RPM. **Singh et al. [7]** showed multi-V ribs with perforation offer a significant boost in thermal results while keeping relatively low friction losses, according to discussion on thermal performance and correlations for Nu (Nusselt Number) and f (friction factor) values various parameters of perforated ribs exposed to continuous heat flux as shown below in Fig. 6. The best alternative in every case was determined to be open area ratio (β) = 0.27, and DPPFSOLAR AIR HEATER with perforation outperformed the smooth channel. The greatest increment in Nu/Nu_s and f/f_s were seen 9.66 and 12.31 times, respectively, in comparison to smooth duct. With an open area ratio (β) = 0.27, the ideal THPP reading was found to be 3.96. Additionally, correlation is constructed for Nu and f within the permissible ranges of ±14% and ±7% deviation lines for the geometry and operational parameter.

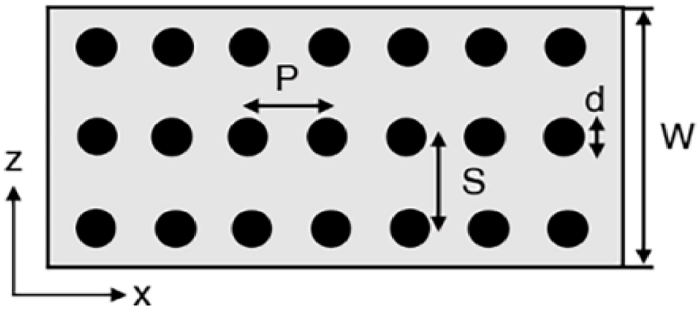

Fig. 5. Geometry and shape of vertical cylinder ribs [6].

Fig. 6. Orientation of plate [7].

Wei-Jie Su and Yao-Hsien Liu [8] experimented and measured heat transfer and friction factor in V-shaped, X-shape, and upstream and downstream cutback X-shaped ribs. The experiment resulted in higher nusselt number. Despite the wide rib spacing, the X-shaped ribs generated the maximum heat transfer. The pressure loss brought on by the whole X-shaped ribs was successfully mitigated by the cutback X-shaped ribs. As a result, the upstream cutback X ribs and V-shaped ribs (P/e = 10) had the best thermal performance. Regardless of the rib design, the Nusselt number ratios were higher near the shorter base in the trapezoidal channel. It should be remembered that the height and spacing ratios of the ribs should not be ideal, and a thorough parametric analysis might be able to improve the rib performance. **Agrawal and bhagoria [9]** used artificial roughness with an area in the absorbent plate, an experimental investigation of the heat transfer and fluid flow characteristics of the solar air heater was conducted. Discrete rib roughness was applied in a double reverse arc way with mass flow fluctuations ranging from 3000 to 14000 in the Reynolds number. In order to achieve the qualities of heat transfer and fluid flow, the range of roughness parameters, such as the first used for the constant value of α of 600 and p/e from 6.67, 8.33, 10, 11.67, and the second used for the fixed value p/e of 8.33 along with the arc angle change, α of 300, 450, 600, and 750. **Eren et al. [10]** showed that when compared to a smooth duct, the heat transmission rate was greatly increased by perforated ribs. Compared to smooth surfaces, surfaces with perforated ribs conveyed an average of more heat. Holes caused the boundary layer to become disturbed, and the separated and reattached flows increased the turbulence. Regarding the correlations between the Nusselt number and the friction factor, the current data fairly accord within the ±12% deviance. The greatest variation in the mean Nusselt number between a smooth and a perforated rib discovered to happen at Re=36362, where it amounted to 34.1%.

Karwa et al. [11] presented the findings of an experimental study on heat transfer and friction for air flow in rectangular ducts with recurrently chamfered rib-roughness on a single broad wall. The rectangular conduit under investigation had aspect ratios of 4.8, 6.1, 7.8, 9.66, and 12.0. The remaining three walls were insulated, and the roughened wall receives consistent heating. These boundary conditions nearly matched the specifications of solar air heaters. Reynolds numbers ranging from 3000 to 20 000, relative roughness heights between 0.0141 and 0.0328, relative roughness pitches of 4.5, 5.8, 7.0, and 8.5, and rib chamfer angles of -15, 0, 5, 10, 15, and 18° are the range of parameters that were examined. These characteristics correlate to roughness Reynolds numbers between 5 and 60. **Jaurker et al. [12]** researched on the impact of artificial roughness with rib grooves on the heat transfer coefficient, friction factor, and thermo-hydraulic efficiency of solar air heater ducts with one main wall was roughened with rib grooves. Fig. 7 represents the geometry of rib roughness. Research was done on the impact of relative roughness pitch, relative roughness height, and relative groove position on the friction factor and heat transfer coefficient. The primary findings concluded that the presence of rib grooved artificial roughness resulted in a Nusselt number that was up to 2.7 times higher than that of the smooth duct and a friction factor that was up to 3.6 times higher. The relative roughness pitch of approximately 6.0 was the maximum for heat transfer, and it decreased on both sides of the pitch. Similarly, it was seen for the friction factor. The groove position to pitch ratio of 0.4 was the ideal condition for heat transfer; on either side of this ratio, the friction factor and the Nusselt number decreased. Nusselt number and friction factor statistical relationships were established as functions of pitch, Reynolds number, rib-groove position, and rib height (or depth). It was discovered that these correlations accurately predicted the Nusselt number and friction factor values, with average absolute percentage deviations of 3.16% and 2.73%, respectively. It was discovered that the rib-grooved configuration provided the best thermo-hydraulic performance and may therefore be used to increase heat transmission. **Han and Zhang [13]** showed that for Reynolds numbers ranging from 15 000 to 90 000, the impact of the broken rib orientation on the local heat transfer distributions and pressure drop in a square channel with two opposing in-line ribbed walls was examined. The square channel had a length-to-hydraulic diameter ratio of 20 and was made out of ten separate copper parts. The ratio of rib height to hydraulic diameter is 0.0625, while the ratio of rib pitch to height is 10. Based on the results, it was concluded that the 60° parallel broken rib or 60° V-shaped broken rib enhanced heat transfer more than the 45° parallel broken rib or 45° V-shaped broken rib, and more than the 90° breaks. The heat transfer enhancement of the parallel "broken rib" or V-shaped "broken rib" was 2.5–4 times that of the previous parallel 'continuous rib' or V-shaped 'continuous rib' with 2–3 times heat transfer augmentation for the same amount of 7–8 times pressure drop penalty.

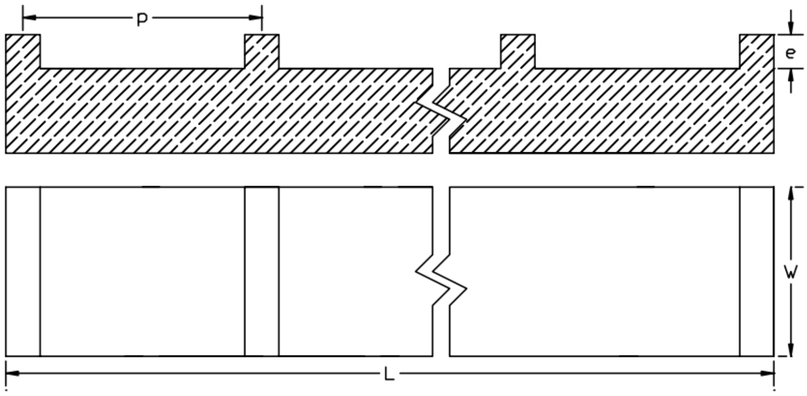

Fig. 7. Rib roughness geometry [13].

Momin et al. [14] showed that as the Reynolds number increased, the Friction factor decreased and the Nusselt number increased. When compared to results obtained for smooth absorber plates, the values of the friction factor and Nusselt number were significantly higher. Fig. 8. shows the diagram of 30 V-shaped ribs. This is because roughness resulted in different changes to the fluid flow properties, which lead to flow separations, reattachments, and the production of secondary. For an angle of attack of 60 degrees, it was discovered that the maximum enhancement of the Nusselt number and friction factor due to the provision of artificial roughness is 2.30 and 2.83 times that of smooth duct, respectively. It was shown that the highest values of the friction factor and Nusselt number correlate to the same angle of attack. An ideal angle of attack appeared to be produced by the separation of the flow, the secondary flow brought about by the presence of V-shaped ribs, and the movement of the ensuing vortices. It was found that the V-shaped ribs increased the values of Nusselt number by 1.14 and 2.30 times over inclined ribs and smooth plate case at Reynolds number of 17034, respectively, for relative roughness height of 0.034 and angle of attack of 60. It indicates that for comparable working conditions, V-shaped ribs have a clear benefit over inclined ribs. When the experimental Nusselt number values were compared to the correlation's predicted values, it was seen that 214 out of 224 data points fall within the 10% deviation range, while 219 out of

224 data points fall within the 10% range in the case of the friction factor. Thus, it can be said that the correlations were rather good in predicting the friction factor and Nusselt number for the roughened duct. **Lanjewar et al. [15]** experimented that as Reynolds number rises, the Nusselt number rises while the friction factor falls. The Nusselt number and friction factor values were greater than those for a smooth absorber plate. The given Fig. 9 shows the geometry of W-shaped ribs at 60^o angle. This resulted in flow separation, reattachments, and the creation of secondar due to changes in flow properties brought on by roughness. For an angle of attack of 60, the maximum enhancement of the Nusselt number and friction factor due to the provision of artificial roughness was found to be 2.36 and 2.01 times that of the smooth duct, respectively. The Nusselt number and friction factor maximum values correlated with the same angle of attack. The ideal angle of attack was produced by the combination of flow separation, secondary flow brought on by the presence of W-shaped ribs, and vortex movement. When the experimental Nusselt number values was compared to the correlation-predicted values, 106 out of 112 data points fall within an approximate deviation range of 11%, while 112 out of 112 data points fall within an approximate deviation range of 5% in the case of the friction factor. Thus, correlations for the prediction of the friction factor and Nusselt number was said to be rather excellent. At a 60 degree angle of attack and a relative roughness height of 0.03375, W-shaped ribs increased the Nusselt number value by 2.21 times compared to a smooth plate with a 14,000 Reynolds number.

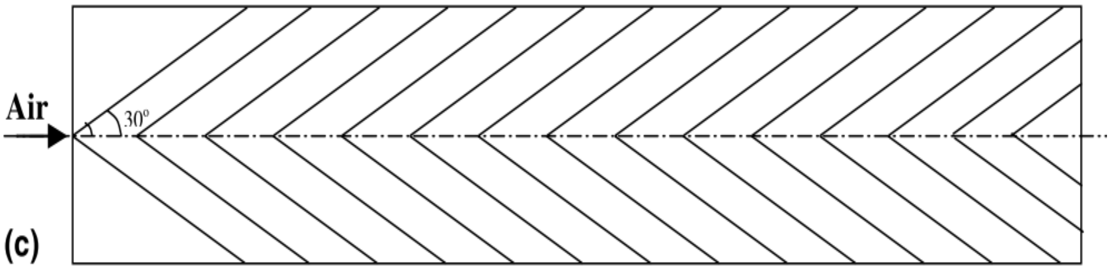

Fig. 8. Schematic diagram of 30 V-shaped rib [15].

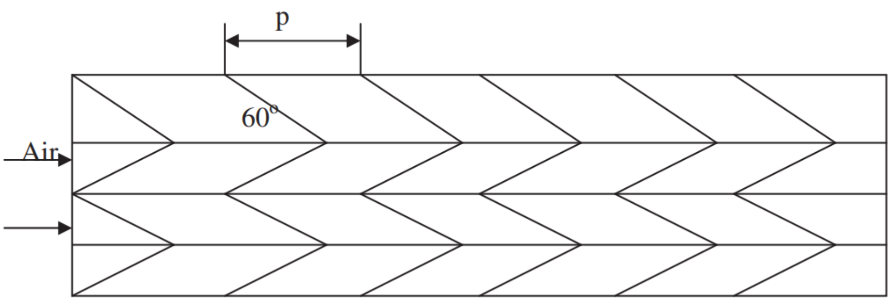

Fig. 9. Schematic diagram of 60^o W-shaped ribs [16].

Sharma et al. [16] examined a double-pass, roughened solar air heater. Other factors like relative roughness pitch (p/e), relative roughness height (e/D), and angle of attack (α) varied correspondingly by 5–20, 0.022–0.044, and 30°–75°. When the results were compared to those of a smooth absorber plate, a significant improvement in heat transfer and friction was shown. The impact of roughness and operating conditions on Nusselt number (Nu) and

friction factor (f) was also established. Correlations for the Nusselt number and friction factor were also developed using the experimental data. **Hans et al. [17]** found that adding artificial roughness to the absorber plate's underside is a cost-efficient method of enhancing a solar air heater's thermal efficiency. Various experimental studies were conducted to enhance the heat transmission from the absorber plate to the air flowing in solar air heaters. These studies involved various types of roughness components. He examined the impact of multiple v-rib roughness on the friction factor and heat transfer coefficient in a solar air heater duct that was intentionally roughened. The experiment included the following ranges of values: Reynolds number (R_e) from 2000 to 20000; relative roughness pitch (P/e) from 6 to 12; angle of attack (α) from 30° to 75°; and relative roughness width (W/w) from 1 to 10. Data on heat transfer and fluid flow properties of a rectangular duct roughened with several v-ribs were gathered through extensive experimentation. These experimental results were used to build correlations between the roughness geometry and flow parameters and the Nusselt number and friction factor. For the range of parameters taken into consideration, the greatest amplification of the Nusselt number and friction factor caused by the existence of such an artificial roughness was found to be 6 and 5 times, respectively, in contrast to the smooth duct. **Karmare et al. [18]** described an experimental study of the heat transfer capabilities of a rectangular duct that transfers heat to the air passing through it by using metal grit ribs on one broad wall as roughness elements. Fig. 10 shows the roughened surface collector. An even heat flux is applied to the broad wall. For the flow range of Reynolds numbers 4000–17,000, the impact of metal grid ribs' relative length, height, and pitch on heat transfer and friction factor was investigated. For the range of Re (4000–17,000), l/s (1.00–1.72), e/D_h (0.035–0.044), and p/e (12.5–36), the presence of metal grit ribs on the collector surface of the duct results in up to a two-fold augmentation in the Nusselt number and a three-fold enhancement in the friction factor. The heat transfer performance and heat transfer coefficient was maximum on Plate No. 05 (roughness parameters: l/s = 1.72, e/D_h = 0.044, p/e = 17.5), while the friction factor is highest on Plate No. 06 (roughness parameters: l/s = 1.72, e/D_h = 0.044, p/e = 12.5). For the range of parameters examined, Plate No. 05 with roughness values of l/s = 1.72, e/D_h = 0.044, and p/e = 17.5 exhibits optimal performance.
(It was discovered that the friction factor had grown by 213% and the Nusselt number had improved by 187%).

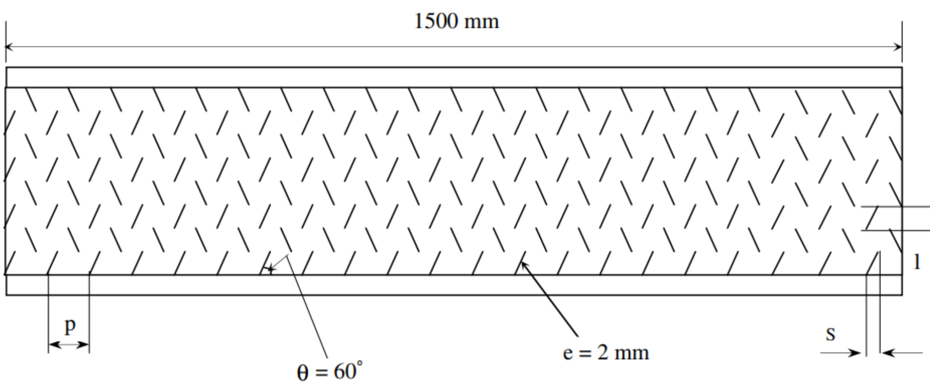

Fig. 10. Geometry of roughened surface collector [22].

Jin et al. [19] investigated on the fluid flow and heat transmission in a solar air heater that had several V-shaped ribs spaced apart on the absorber plate. Three-dimensional simulations were run for several rib configurations with variable Reynolds numbers, stagger distances, and rib heights, pitches, and angles of attack. Compared to the same inline arrangement, staggered multiple V-shaped ribs offered superior heat transfer, with maximum enhancements of 26% and 18% for the average Nusselt number and thermohydraulic performance factor, respectively. The fundamental flow structure for the staggered ribs remains the primary vortex with interrib subsidiary vortex, much like in the inline case. At the ideal stagger distance, the gap flow maximizes heat transfer efficiency by inducing two opposing effects on heat transfer. In the range of parameters, the staggered ribs' maximum thermohydraulic performance factor was 2.43.

III. PROTRUSIONS AS ARTIFICIAL ROUGHNESS

Soi et al. [20] examined the effects of various protrusion shapes, locations, and heights on solar air heater duct performance over a variety of parameters through an experimental inquiry. When compared to non-spherical protrusions, spherical protrusions resulted in higher heat transfer coefficients and friction losses. Fig. 11 shows geometry of protrusions and different shapes of protrusions. In comparison to smooth duct, the Nusselt number was found to be 3.9 times greater and the friction factor was found to be 1.8 times higher. At relative protrusion position (w/W) of 0.166, relative roughness height (e/D) of 0.036, and sphericity (ψ) of 1, the Nusselt number exhibits the maximum augmentation. Nusselt number and friction factor correlations were found using the experimental data, and those were utilized to assess solar air heater performance. v **Sethi et al. [21]** showed the impact of artificial roughness on heat transfer and friction characteristics in solar air heater ducts with dime-shaped roughness elements arranged in an arc pattern on the absorber plate was examined experimentally for a variety of system and operating parameters. An arc angle (α) range of 45–75°, a relative roughness pitch (p/e) of 10–20, a relative roughness height (e/D) of 0.021–0.036, and a Reynolds number (R_e) ranging from 3600 to 18,000 were all present in ducts. There had been a noticeable rise in heat transmission and friction loss. Nusselt number and friction factor correlations as a function of roughness parameters and operational parameters was developed using the experimental data. **Saini and Verma [22]** experimentally showed that by adding artificial roughness to the underside of the absorber plate of a solar air heater duct, the heat transfer coefficient between the air and absorber plate could be significantly raised. Under the current project, an experimental investigation was conducted to look into how operational parameters and roughness affect heat transfer and the friction factor in a roughened duct with dimple-shaped roughness geometry. Relative pitch (p/e) from 8 to 12, relative roughness height (e/D) from 0.018 to 0.037, and Reynolds number (Re) from 2000 to 12,000 were all examined in this inquiry. Values of the Nusselt number (Nu) and friction factor (f) were also calculated for various values of roughness and operating parameters based on the experimental data. Values of the Nusselt number and friction factor were compared with those of smooth ducts under identical flow circumstances in order to ascertain the enhancement in heat transfer and increment in friction factor. When such artificial roughness geometry was used, correlations for the Nusselt number and friction factor were also found for solar air heater ducts.

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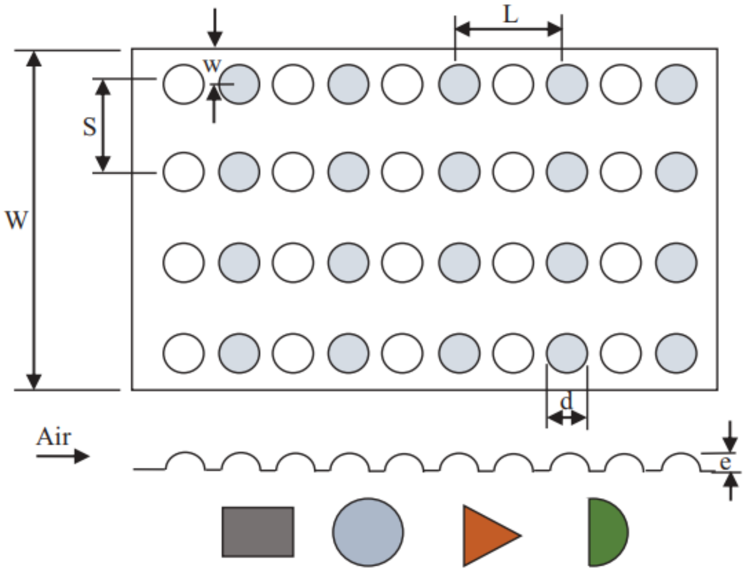

Fig. 11. Geometry of protrusions and different shapes of protrusions [4].

Perwez and Kumar [39] carried out an experimental study to compare the thermal performance of a flat plate solar air heater (FPSAR) and a spherical dimple plate sun air heater (SDPSAR) under various environmental circumstances. The air mass flow rate used for the investigation ranged from 0.009 kg/s to 0.028 kg/s. The findings demonstrate that, at 1.51 to 1.64 times higher than the equivalent FPSOLAR AIR HEATER, the SDPSOLAR AIR HEATER exhibits the maximum heat transmission rate. For a mass flow rate of air of 0.009 kg/s, the maximum rise in the SDPSOLAR AIR HEATER's output temperature was approximately 4.6°C higher than that of the similar FPSOLAR AIR HEATER. The SDPSOLAR AIR HEATER's immediate thermal efficiency was between 23.45% and 35.50% higher than that of the matching FPSOLAR AIR HEATER. **Alam et al. [50]** Showed the properties of the net effective efficiency of a conical protrusion rib-roughened absorber surface in a solar air heater. The roughness of the conical protrusion rib had a major impact on the solar air heater duct's net effective efficiency. Fig. 12 shows the protrusion rib roughness. At e/D of 0.0289 and p/e of 10, an effective efficiency improvement of up to 70.92% was achieved. It was also noted that net effective efficiency depends on insolation. When the insolation rose from 600 W/ m^2 to 1000 W/ m^2, the highest effective efficiency increased from 69.82% to 70.92%. For temperature increase parameter ranges of $0.00369 < \Delta T/I < 0.00463$ Km^2/W, $0.00463 < \Delta T/I$ 0.00608 Km^2/W, $0.00608 < \Delta T/I$ 0.00691 K m^2/W, and $0.00691 < \Delta T/I$ K m^2 /W, respectively, the optimal relative rib heights have been determined to be 0.020, 0.0289, 0.036, and 0.044. The best net effective efficiency has also been obtained for temperature increase parameters within the ranges $0.00365 < \Delta T/I < 0.00562$ K m^2/W and $0.00365 < \Delta T/I$ K m^2/W, respectively, with relative rib pitches of 12 and 10. When $\Delta T/I > 0.00789$ K m^2 /W, a special pair of optimum relative rib height of 0.44 and relative rib pitch of 10 was observed, independent of the insolation value.

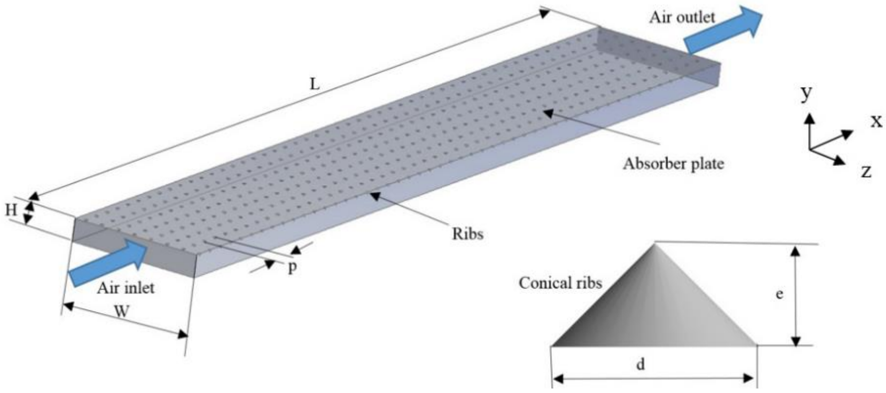

Fig. 12. Protrusion rib roughness [50].

IV. CONCLUSION

An attempt has been made to report several artificial roughness kinds employed in solar air heaters to enhance their performance in the current research. The experimental tests conducted by different researchers and the methods of creating artificial roughness have been studied. Various forms are being used such as ribs, wires, mesh, protrusions etc. Artificial roughness has been found to be an effective way to increase the thermal efficiency of solar air heaters. Many such investigations can be further carried to explore in the are of artificial roughness including cavities arranged in different patterns.

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