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Enhancing the Performance of a Solar Air Heater with Arc-shaped Artificial Rib Roughness

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Abstract

For the purpose of drying agricultural commodities, heating rooms, seasoning timber, and curing industrial things, the Solar Air Heater (SAH) is frequently used. Moreover, SAH is the least expensive option available. A purposefully roughened surface can boost heat delivery to SAH fluid in the duct. For the larger part of the last 4 decades, researchers have been conducting studies exploring the possibility of incorporating artificial roughness into SAHs. This paper attempts to describe the numerous roughness geometry types that can be used to artificially roughen SAHs to improve their performance. This article presents the findings of a number of experimental and computational studies that were conducted on SAHs that were roughened utilizing a variety of different forms of arc shaped rib roughness geometry. This article examines the influence of several rib variables on heat transfer and fluid dynamics.

Major Findings: *Solar air heaters benefit from wire rib roughness designs that promote heat transmission and friction. V-rib and arc-shaped geometries had higher heat transmission due to secondary flow cell growth. Roughness patterns like gaped arrangements increase turbulence and mixing flow, improving heat transfer.*

Keywords: *Artificial Roughness, Heat Transfer, Nusselt Number, Reynolds Number, Solar Air Heater*

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1.0 Introduction

The creation and utilization of energy supplies is the foundation upon which human civilization is built. Energy is necessary in every aspect of existence, whether it be for domestic usage, for industrial purposes, or for aspects of life that are fundamental but extremely significant, such as transportation and agriculture. It is clear that energy is highly significant, as evidenced by the fact that it serves as the primary source of power for all of the operations that are carried out in the modern period. In today's world, proper management of energy and the availability of its supply at all times is not only an essential component of our day-to-day lives, but it is also a prerequisite for the development of the nation, as well as for the prosperity and stability of the economy, and for the preservation of the environment. Simply put, the only presence that is all around us is energy. Different kinds of energy include mechanical energy, thermal energy, electrical energy, chemical energy, and nuclear energy. There are also many other types of energy. At the most fundamental level, it is the source of power for a wide variety of activities and processes. Energy is essential to every single business, including agriculture, industry, transportation, communication, medical, and even entertainment. Without it, not a single sector can be considered whole. There are many different businesses that require electricity as a source of energy. For example, agricultural land requires energy from electric sources in order to be irrigated; businesses require energy in order to run machinery. Our homes require energy in order to generate light and heat and to carry out other domestic tasks. In order to emphasize the significance of energy, it is important to note that the economic and technological progress of any nation or organization is essentially dependent on the availability of energy as well as the efficiency with which this energy is utilized. A consistent growth rate is being seen by nations that are able to harness and make appropriate use of various sources of energy. Especially for still-emerging economies, energy shortages might the biggest obstacle to progress. The fossil energy sources (coal, petroleum, and natural gas) were utilized to meet our energy demands for many decades. This is so for our country as well through history. These sources are the primary constituents of the global energy supply as they are the sources through which energy is produced. Hence, themselves being the biggest contributors. But then the restraints and the adverse effects of those fuels give an important purpose for trouble today. But they also have their own risks, the most notable being their limited supply. For example, fossil fuels like coal, oil and natural gas, form over the course of millions of years. And every one of those, of course, has its limitations, as every fossil fuel has its unique potentials. They're releasing lots of GHG in the atmosphere. These GHG are largely carbon dioxide and methane. These gases are responsible for global warming and climate change. Not only are these resources and their consumption stopped, but also their ecosystem is destroyed in a thousand times greater scale. Environmental harm, this is one similar activity which includes destruction of forests soil erosion water pollution *etc*. The energy crisis has emerged as one of the most pressing global issues over the decades. The use of energy has skyrocketed as a result of population boom, urbanisation, and industrialization, likely more than at any time in human history. While demand is not only heterogeneous, the availability of conventional energy sources is limited and these are also evenly distributed. It is possible to see, with moderation, that the energy crisis afflicts a disjointed number of systems. As a result of the delay caused by the lack of energy, the production process in the economy is slowed down, which in turn slows down the development of the economy. When it comes to social issues, the quality of life is negatively impacted since there is a shortage of electricity and other sources of energy, which restricts access to essential services such as education, healthcare, and basic necessities. From the point of view of the environment, the energy crisis also means that an increasing amount of fossil fuels are being used, which further exacerbates the environmental problems that are already present[1-5].

In today's open society, the utilization of renewable resources has become an absolute necessity for effectively managing the energy crisis and environmental challenges. The term "renewable energy" refers to energy that is created *via* the use of renewable energy sources. Renewable energy is an energy that is without limit and is environmentally friendly. If all of these sources are utilized, it has the potential to lessen our reliance on traditional sources of energy and pave the way for a future that is more environmentally friendly in terms of energy. Without a doubt, the most important characteristic of

renewable energy is the natural regrowth that occurs very near to constantly. In addition, renewable energy sources are the only environmentally friendly energy sources that produce virtually no emissions of greenhouse gases. These energy sources not only avoid pollution of the environment, but they also reduce the costs of energy. This is due to the fact that the operational cost of renewable energy generation systems after they have been installed is quite low. These are the additional forms of renewable energy that are relevant in addition to solar power: wind power, hydropower, and geothermal power. Using wind energy, electricity can be generated by the harnessing of wind. Additionally, it is a non-polluting and renewable source of energy. Hydropower is not any different and same it goes for barriers that are large enough to harvest hydro energy. Because of this, it is one of the cheapest and most reliable energy transportation modes. This also relates to the other fields, such as geothermal energy, and biomass energy, and all of the related activities that try to grow plants and grow animal. Unlike geothermal energy, extracted from the heat of the earth, biomass energy is obtained from residues such as agricultural and natural waste. This could bring high benefits for these types of energy used in a considerate manner; namely energy restoration, waste management, and environmental protection[6-11].

Even though renewable energy has many benefits, there are some challenges involved in its implementation. The highest barrier to entry is the initial cost. It will cost you a fortune to place a big bet on the solar panels, windmills and hydropower projects. However, there is one more challenge that should be taken care of quickly-sustainability and renewable resources storage. This issue is a great solution for solar energy due to the fact that it can easily run for an extended period of time without interruption. This includes some form of solar power that is only available in a narrow window of time each day, and storing it for the evening hours has proven to be a difficult problem to solve. Despite all the difficulties mentioned above, now is the time to change to clean energy circumstances. To use renewable most effectively, standards and guidelines must be established. Getting here will take a collective effort among regulators, industry, and us[12].

In comparison to other forms of renewable energy, solar power is the most important. This is the most accessible and one of the most affordable forms of energy that we have because the light of the sun is present everywhere on our world. Applications of solar energy despite the fact that solar energy may be utilized in a variety of ways, including the creation of electricity through the utilization of solar panels, the production of hot water through the utilization of solar water heaters, and the preparation of food through the utilization of solar cookers. As one of the most significant benefits of solar electricity, the fact that solar energy solutions may be obtained virtually anywhere is a significant advantage. In both urban and rural settings, assistance with it is provided. Solar energy is the ideal kind of energy for places that have a prevalent scarcity of electricity, such as the majority of rural areas. This is because of the extraordinary potential of modest power plants. The fulfillment of domestic demands, as well as needs in agriculture and cottage businesses, can benefit from its utilization. Considering the growth of urban centers, solar energy is not only important for the generation of electricity at the utility scale, but it also plays a role in improving energy efficiency in buildings. Solar power systems, in addition to this, serve as an efficient means of protecting the environment. Almost no emissions of greenhouse gases because it is the most environmentally friendly method of producing electricity. Additionally, it reduces our reliance on fossil fuels and helps to slow the progression of climate change[13,14].

Solar air heaters are another straightforward and uncomplicated technology that has the ability to heat the air by making use of the energy that is derived from the sun's beams (Figure 1). It is an excellent source of delivering clean and green energy, primarily fulfilling the requirements of the commercial, industrial, and residential sectors. A solar air heater is a device that allows air to be heated and then utilized for a variety of applications. The air is heated by passing through a solar collector that is heated by the sun. Solar air heater is that one remarkable invention when it comes to the field of energy that actually aids in the resolution of the energy genre and also helps in mitigating the adverse effects that traditional energy resources produce. How is such a system, the operation of this in brief has spelt out below. Solar rays heat the solar collector's absorbent surface which in turn warms the cold air entering the collector. This warm air then exits the building through either

natural or mechanical vents. This hot air can be used for heating of building, drying of crops, providing industrial heat, and tempering of shelter for livestock. This hot air can do all of this. Airflow at a higher efficiency cannot spread, transparent cover and an absorber plate with insulation depending upon user needs and the location, one can choose from a range of different types of solar air heaters. These are direct flow, indirect flow, and double way flow heaters. Active systems- are those which use fans and blowers to effectively increase the flow of air, whereas passive systems are those which rely on air flow through natural means. Due to this diversity, it can be applied for a variety of needs, from small domestic, such as homes and small industrial homes, to large-scale commercial uses. Heating air with a solar air heater is one of the best ways to heat your air in an environmentally friendly manner. Furthermore, it is fully fueled with clean and renewable energy sources, and, therefore, does not emit greenhouse gases. Due to the fact that it is charged by solar energy, its overhead costs are relatively low. It also helps to lessen reliance on the traditional sources of energy and makes the live more independent with respect to energy. This is an extremely valuable feature for spots where believing fuels are expensive or non-existent. On top of this, it is extremely low-interest. First, solar air heater has very high initial set-up costs and the efficiency of a solar air heater may vary greatly depending on the weather type. This use is limited, however, to clear days and will never be used in fog or overnight. Secondly, to be placed for heavy-duty applications, it needs a vast space. However, these concerns are slowly being solved as the technology progresses. Using new designs of today and new materials, you can now do it cheaper and easier than ever. Apart from that, there will a rise in toll of solar air heaters within the extended time line. This is already being promoted in a variety of governments and organizations through the provision of a variety of plans and subsidies. In addition to that, it provides a solution to the energy crisis, and the use of this technology will as well contribute to the reduction of the carbon footprint. One of the most significant opportunities for energy efficiency and environmental sustainability is presented by the fact that the tool is easily accessible to the general public. This is because the tool has the capacity to function both in rural areas and in urban centers. Solar-powered air heaters are not only a clean and long-term answer to environmental issues, but

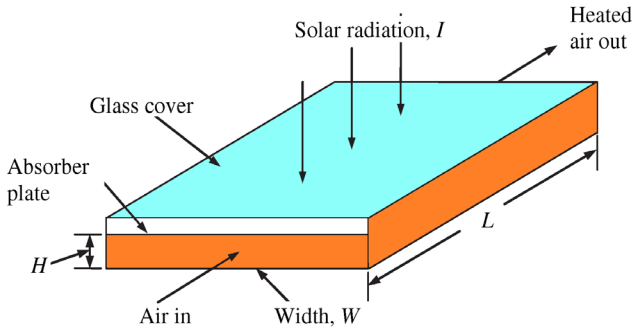


Figure 1. SAH[17].

they are also a permanent solution to the ever-increasing demand for energy. Considering that it is a strategy for long-term investments, it not only reduces expenses but also serves as a stepping stone on the path to a world that is clean and green. Not only does the widespread usage of renewable energy resources provide a solution to the energy issue, but it also serves as an efficient approach for achieving sustainable development and achieving energy independence. Within the context of this new phase of energy generation and consumption, solar air heaters are one of the instruments that must be utilized in order to guarantee a safe and environmentally friendly world[15,16].

Numerous investigations have been carried out in order to have a better understanding of the potential for solar air heaters to improve heat transfer capability. The various shapes of ribs, wire coils, twisted tapes, dimpled, corrugated, and grooved tubes, combined and compound turbulators, and so on are all examples of the layouts that are included in this category[18-30]. Alterations of varying kinds are made to the absorber plates in order to enhance the efficiency of the SAH. The incorporation of artificial roughness is one of these alterations. The ribs introduce more turbulent flow, which in turn, causes disruption to the thermal boundary layer and enhance heat transfer. Several computational models have been developed in addition to experimental research in order to acquire a better understanding of the process that enhances heat transfer in the SAH in the presence of ribs[31-38]. The extreme heights due to large pressure drops, though, will have a deleterious effect on efficiency. The ribs can take on a geometric shape (triangular, sinusoidal, or a combination of them), which is an additional factor affecting heat

transfer. Even the spacing and orientation of the ribs can be optimized in order to achieve extra heat transfer for the same air mixing amount which is advisable. These ribs can be aligned, sloped, or staggered. Moreover, ribs can be used with other surface modifications like corrugations or vortex generators to increase convective heat transfer. This is done to ease the transfer of heat. Optimizing solar air heater requires a trade-off between design of the ribs to achieve ideal pressure drop and heat transfer performance. It goes without saying that this step is also vital to achieve the maximum possible extraction of potential solar radiation energy without significantly altering the drag flow impedance that these ribs impose. This research paper aims to find the best configuration of arc shaped ribs to improve the performance of the system. In its later segments, the study discusses various types of arc shaped ribs and their impact on promoting heat transfer. By using various types of arc shaped ribs, the best possible heat transfer can be reached. The finding of the best rib design that maximizes heat transmission while having a minimal impact on rising pressure drop is made possible as a result of this[39-43].

Experimental and Numerical Investigations

In relation to SAHs, the solitary heated wall must be considered in terms of roughness factors, as it is the only wall subjected to solar radiation. To accomplish this, SAHs are constructed as rectangular conduits featuring 3 smooth sides and 1 rough wall. The exchange of thermal energy of this conduit differs from those of roughened annular tubes, circular tubes, and channels with 2 oppositely roughened walls. As with other-shape ribs, the arc ribs work similarly but there are differences in their configurations and they also have variations on them; unlike other-shape ribs, arc's ribs provide varying degrees of slope to both primary flow and vortex. As a further variation on the arc shape, the S shape can be seen. Roughness and flow parameters affected by the arc rib, as shown below, were investigated by a number of researchers.

Saini and Saini employed arc-shaped roughness in their examination of SAH duct performance. In addition, they established empirical correlations for Nu and f based on the geometrical properties that were explored (Figure 2)[44].

For the purpose of exergy study, Sahu and Prasad analysed a rectangular SAH duct having the rib shape of an arc. Based on their investigation, the several criteria that are being taken into account lead to a gain in energy efficiency that can reach up to 56 % (Figure 3)[45].

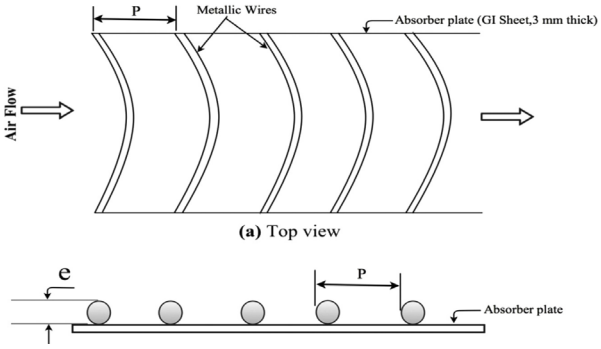


Figure 3. Arc shaped ribs[45].

Sahu and Prasad designed an Entropy Generation Minimisation approach (EGM) that minimised all roughness geometry parameters with the least amount of irreversibility[46]. This was in addition to their investigation

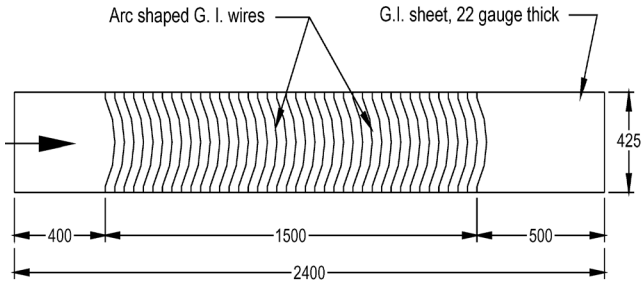


Figure 2. Arc shaped ribs[44].

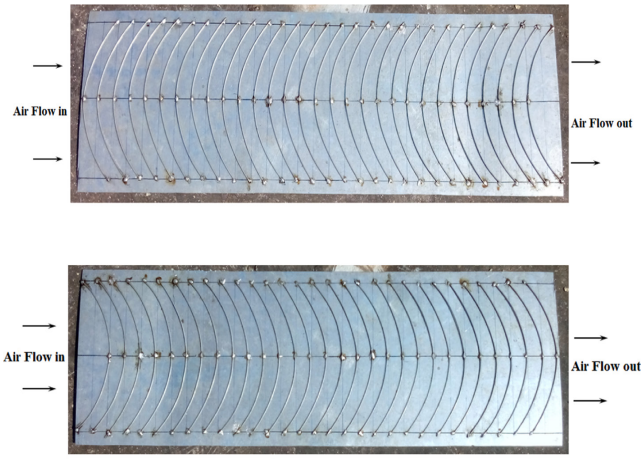


Figure 4. Arc shaped ribs[46].

of a second law-based Entropy Generation Analysis (EGA). As part of their research, Ghritlahre, Sahu analysed the geometry of continuous arc ribs from the apex upwards and compared it to the geometry of continuous arc ribs from the apex downwards[47]. After careful consideration, it was determined that an apex-up rib plate offers superior thermal performance in comparison to an apex-down rib plate (Figure 4).

To improve heat exchange, Hans, Gill evaluated the surface roughness of solar air heater ducts using broken arc geometries[48]. The experiment encompassed a variety of geometrical roughness parameters, including W/H, P/e, e/D, α, d/w, g/e, and Re. Differences between smooth surfaces and continuous arc-shapes are 1.19 and 1.14 times larger in Nu and f increments, respectively (Figure 5).

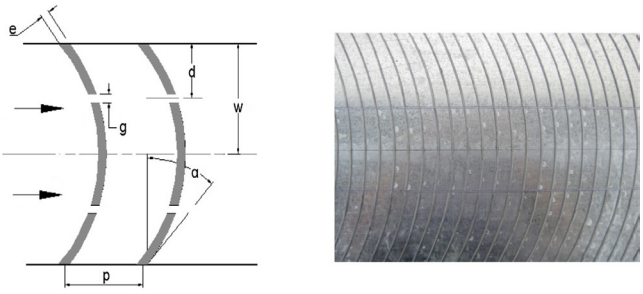


Figure 5. Arc shaped ribs[48].

The investigators Azad, Bhuvad analysed discrete arc rib absorber plates numerically and experimentally[49]. Results showed that geometries with distinct arc ribs performed better than those with V-ribs. Bhuvad, Azad employed apically orientated discrete arc ribs to enhance the efficiency of SAHs (Figure 6)[50].

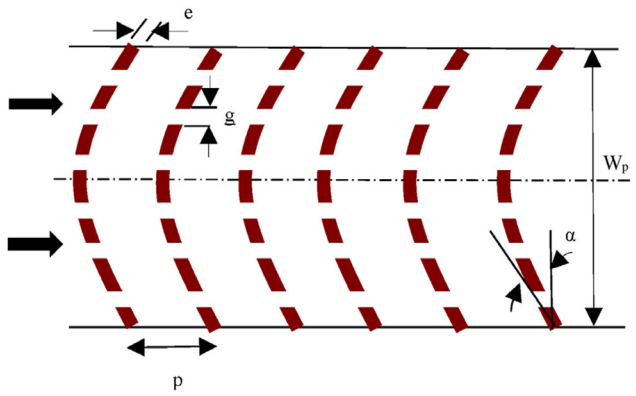


Figure 6. Arc shaped ribs[50].

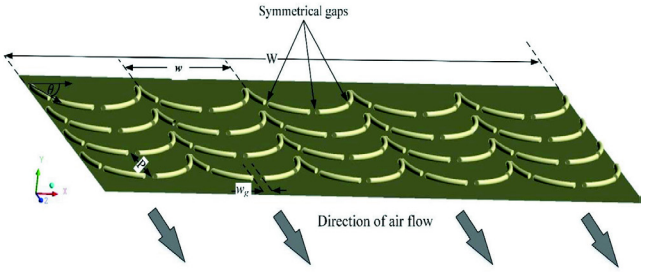


Figure 7. Arc shaped ribs[51].

Using patterns of multiple arc rib roughness in respect to the gap, generalised correlations for the Nu and f are developed by Kumar, Goel (Figure 7)[51].

The effect of gaps was investigated by Jain, Agrawal using arc-shaped roughness, with Ng varied between 2 and 5, and I maintained at 1000 W/m^2. Arc gaps, which limit the expansion of the viscous sub layer, allow more chances for secondary flow mixing and produce better outcomes than continuous arcs[52]. The most optimal thermo-hydraulic performance

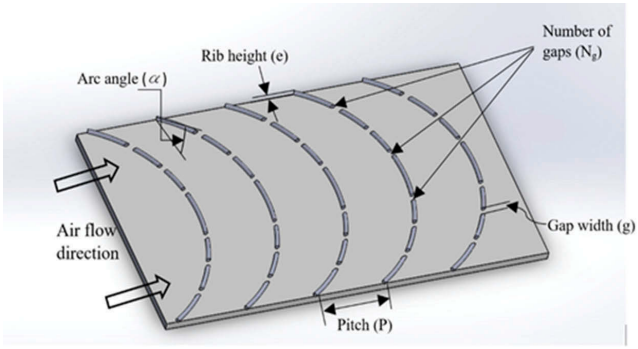


Figure 8. Arc shaped ribs[52].

was achieved at a Ng = 3 value of approximately 2.75 (Figure 8).

Singh, Varun conducted an experiment to determine the effects of various arc-shaped rib features on heat transport and additional SAH characteristics. They used Re between 2200 and 22000, e/ D values between 0.018 and 0.045, α between 30° and 75°, W/w between 1 and 7, and P/e varied between 4 and 16. In comparison to the smooth plate, they found that the increments in Nu and f for roughness with many arcs were around 5.07 and 3.71, respectively. Additionally, they have discovered a connection between f and the Nu number (Figure 9).

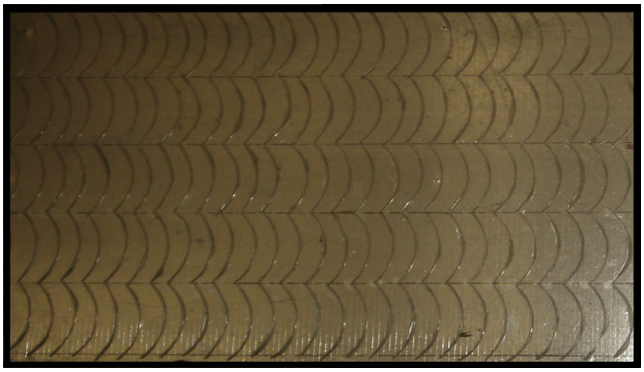


Figure 9. Arc shaped ribs[53].

In order to enhance heat transmission in a 12 aspect ratio SAH duct utilising S-geometry, the sun collector plate was intentionally roughened[54]. The chosen geometrical roughness parameters were 0.022-0.054 for e/D, 30°-75° for α, 4-16 for P/e, 1 to 4 for W/w, and 2400-20,000 for Re. According to experimental research, the maximum increment in Nu and f occurs at 60°. At its peak, the S-shape geometry had a THPP of 3.34 (Figure 10).

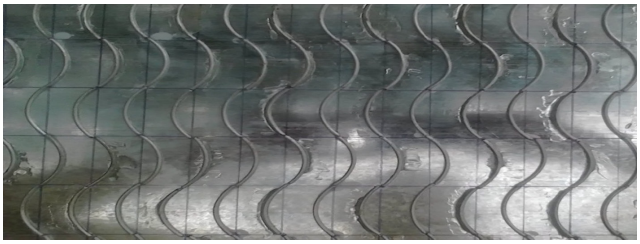


Figure 10. S shaped ribs[54].

In a rectangular channel, several arc shapes with gaps were evaluated[55]. Raw data from roughness and stream characteristics were used to generate friction factor and Nu correlations (Figure 11).

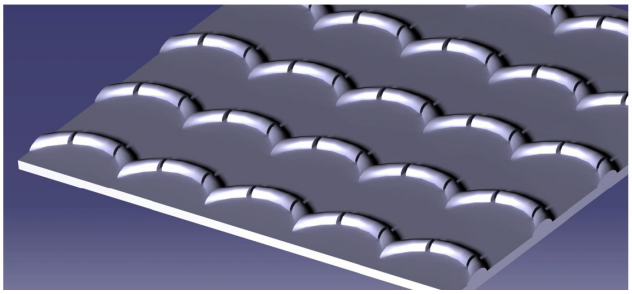


Figure 11. Arc shaped ribs[55].

Using symmetrical arc gaps and staggering roughness elements, Ambade and Lanjewar evaluated the maximum thermal enhancement ratio of 1.41 on a solar collector plate[56]. In order to assess the hybrid structure of broken ribs and staggered ribs, Gill, Hans have performed an experimental and computational investigation[57]. According to their findings, the hybrid combination increased THPP at a maximum rate of 2.33 times more than smooth SAH and 1.22 times greater than broken arc ribs. Additionally, they have discovered a connection between f and the Nu number (Figure 12).



Figure 12. Arc shaped ribs[57].

Wang, Liu investigated the performance of S-shaped ribs in a SAH. Based on the Reynolds number, relative gap spacing, relative rib width, and spacing, the Nusselt number of the SAH was calculated (Figure 13)[58].

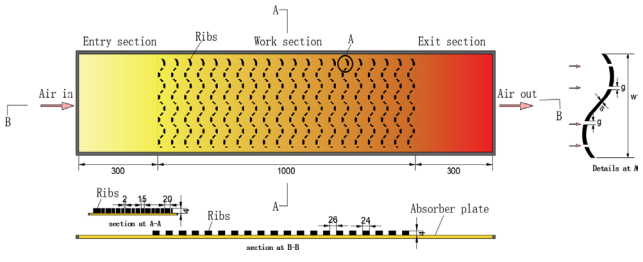


Figure 13. S shaped ribs[58].

Yadav and Lanjewar study the effect of variation in relevant parameters on staggered rib arc roughened solar air heater ducts. In the experiment conducted by Yadav and Lanjewar the staggered rib lengths and surface roughness of arc forms were examined concerning staggered rib lengths. The study primarily examines staggered rib lengths within a specific Reynolds number to assess SAH performance[60]. Table 1, Table 2 and Table 3 show parameter used enhancement in *Nu* and enhancement in *f* respectively.

Table 1. Parameter used

S. No.	Roughness Geometry	P/e	e/D	α
1	Arc shaped ribs[44]	10	0.0422	30°
2	Arc shaped ribs[45]	10	0.0422	30°
3	Apex up continuous arc rib[47]	10	0.0395	60°
4	Broken arc shape[48]	10	0.043	60°
5	Apex-down discrete arc rib[49]	10	0.045	30°
6	Apex-up discrete arc ribs[50]	10	0.045	30°
7	Symmetrical gaps in multiple arc rib[51]	8	0.045	60°
8	Multiple gap arc rib[52]	10	0.043	60°
9	Multiple arc shaped ribs[53]	8	0.045	60°
10	S shaped roughness[54]	8	0.043	60°
11	Multiple arc rib with gap[55]	8	0.045	60°
12	New symmetrical gap arc geometry and staggered element[56]	10	0.0433	30°
13	Hybrid configuration of broken arc and staggered rib[57]	10	0.043	30°
14	S shape rib with gap[58]	20		
15	Broken symmetric arc with staggered element[59]	10	0.045	30°
16	Discrete arc combined with staggered element[60]	10	0.04545	30°

3.0 Results

Various experimental and numerical investigations were conducted out on artificially roughened solar air heaters. The results obtained from different studies are presented in the following Tables.

Table 2. Enhancement in Nusselt number

S. No.	Roughness Geometry	Enhancement in Nusselt Number
1	Arc shaped ribs[44]	3.80
2	Broken arc shape[48]	2.63
3	Apex-down discrete arc rib[49]	2.26
4	Apex-up discrete arc ribs[50]	2.92
5	Symmetrical gaps in multiple arc rib[51]	5.76
6	Multiple gap arc rib[52]	3.75
7	Multiple arc shaped ribs[53]	5.07
8	S shaped roughness[54]	4.64
9	Multiple arc rib with gap[55]	5.85
10	New symmetrical gap arc geometry and staggered element[56]	2.18
11	Hybrid configuration of broken arc and staggered rib[57]	3.16
12	S shape rib with gap[58]	5.42
13	Broken symmetric arc with staggered element[59]	3.23
14	Discrete arc combined with staggered element[60]	2.74

Table 3. Enhancement in fiction factor

S. No.	Roughness Geometry	Enhancement in Fiction Factor
1	Arc shaped ribs[44]	1.75
2	Broken arc shape[48]	2.44
3	Apex-down discrete arc rib[49]	3.87
4	Apex-up discrete arc ribs[50]	3.04
5	Symmetrical gaps in multiple arc rib[51]	6.05
6	Multiple gap arc rib[52]	2.69
7	Multiple arc shaped ribs[53]	3.71
8	S shaped roughness[54]	2.71
9	Multiple arc rib with gap[55]	4.96
10	New symmetrical gap arc geometry and staggered element[56]	3.88
11	Hybrid configuration of broken arc and staggered rib[57]	2.57
12	S shape rib with gap[58]	5.87
13	Broken symmetric arc with staggered element[59]	4.01
14	Discrete arc combined with staggered element[60]	4.93

4.0 Conclusion

There have been improvements in conventional SAH performance brought about by various wire rib roughness geometries. Reviews of these wire rib roughness geometries are carried out in great detail. Heat transfer and friction are both affected by the sequence in which different roughness factors are arranged. For a wide range of roughness geometries, geometrical parameters describe the improvement of heat transmission as Nusselt numbers and the penalties for pressure drop as friction factors. The performance of SAHs can be improved by the employment of a broad variety of roughness geometries, which can be produced, scaled, oriented, and ordered in a variety of various ways. This creates the possibility of improving the performance of SAHs. A suitable selection of the roughness geometry is required by the designer in order to achieve the desired results of increasing the quantity of heat that is conveyed while simultaneously reducing the amount of pressure drop. Plates that have transverse ribs allow for higher heat transfer than plates that are smooth. This is in contrast to plates that are smooth. When compared to the angled roughness geometries, the V-rib and arc-shape roughness geometries formed 2 secondary flow cells, which led to the greatest increase in heat transmission. This is the reason why this is the case. When it comes to the process of heat transmission, the utilization of continuous roughness geometries that contain gaps provides an extra enhancement. Because of the reconstruction of secondary flows, the mixing of flows, and the turbulence that is created by the acceleration of flow across the gap, they are all factors that contribute to the phenomenon. The majority of the investment has been made with single repeating rib roughness geometry from the very beginning of the process. Taking this into consideration, the combination of different roughness geometries offers a plethora of alternatives for investigation.

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