A Review on Roughness Geometries used in Solar Air Heaters for Performance Enhancement

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Abstract
Creating turbulence and providing contrived coarseness in the configuration of ribs of diverse fashions in the fluid flow of a solar air heater and thereby preventing the formation of thermal boundary layer helps in improving the overall achievement of a solar air heater. Solar energy with huge abundance, being renewable and pollution free finds wide range of applications for both domestic and industrial uses. Artificial roughness in the cast of ribs and obstacles of assorted patterns as V shaped, arc shaped, W shaped, transverse ribs etc. raises the heat exchange rate among air and collector plate at the charge of friction factor. In reference to various evaluations put forth by researchers from long time a trial has been executed to contrast various roughened solar air heater ducts and conferred in the literature survey.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>Nu</td>
<td>Nusselt number</td>
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<tr>
<td>Re</td>
<td>Reynolds number</td>
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<tr>
<td>P/e</td>
<td>Relative roughness pitch</td>
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<td>e/D</td>
<td>Relative roughness height</td>
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<td>W/H</td>
<td>Duct aspect ratio</td>
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<td>Pr</td>
<td>Prandtl number</td>
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<tr>
<td>m_a</td>
<td>Mass flow rate of air</td>
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<td>SAH</td>
<td>Solar air heater</td>
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<tr>
<td>f</td>
<td>Friction factor</td>
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<tr>
<td>α</td>
<td>Angle of attack (Degree)</td>
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<td>T_i</td>
<td>Temperature of air at inlet (K)</td>
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<tr>
<td>T_o</td>
<td>Temperature of air at outlet (K)</td>
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<td>P</td>
<td>Roughness pitch (m)</td>
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<td>St</td>
<td>Stanton Number</td>
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<tr>
<td>e</td>
<td>Height of roughness element</td>
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<tr>
<td>e⁺</td>
<td>Roughness Reynolds number</td>
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<td>R (e⁺)</td>
<td>Momentum Transfer Roughness function</td>
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Introduction
The requirement of energy across the globe is increasing at a distressing rate. The conventional sources of energy may no longer be able to meet the requisite demands. India being the second most populous country in the world having 20% of the total world population has a per capita energy consumption of 400 KWh. Hence, the need of hour is to hunt for the sources of energy which can lost longer and wouldn’t harm any forms of lives on the planet earth. Solar energy being a renewable and non-conventional source of energy like wind energy, tidal energy and geothermal energy is a topic of main concern. Conventional sources of energy like Coal and Petroleum products were formed inside the earth’s crust for millions of years and will be exhausted in near future. To save the coming generations we ought to focus on renewable sources of energy. Solar energy due to its quantitative
abundance has a total energy potential of about 10,000 times the present world energy demand with average intensity of solar radiation in our country as 2100 KWh/m².

Solar energy originating from sun is evolved by a series of chemical reactions that convert about 65*10⁷ tons of Hydrogen to Helium every second. The energy from sun at a distance of 1.5*10⁸ Km reaches the surfaces of collector plates installed on buildings and structures in beam and diffused forms of electromagnetic radiations. The former is called as direct radiation since they don’t change direction while travelling while as latter are subjected to scattering, absorption, re-radiations and re-reflections in the atmosphere. The rate at which energy is received from the sun on a unit area normal to solar beam is 1353 w/m² and it governed by:

$$I_{sc} = \frac{I_{sc}}{1+ 0.0333 \cos \frac{360n}{365}}$$

Where n is number of day of the year and $I_{sc}$ is standard value of Solar Constant

Solar energy finds a wide range of applications which include heating and cooling of buildings, cooking of food, distillation of water, green houses, solar refrigeration and air conditioning and power generation etc. Solar energy being free of cost, environment friendly and having a high potential is accompanied with the limitations of high cost of collector plates, being intermittent in nature and not reliable since could be interrupted by clouds, rains and dust etc.

1.1 Solar Collectors

A solar absorber plate is a virtual heat exchanging device which converts radiant solar energy into some useful form. The energy from sun in the form of electromagnetic waves is exchanged with the fluid (air) in a solar air heater. Solar collectors usually have two types as concentrating collectors and flat plate collectors. The former are more efficient since a high intensity of solar radiation is made to incident on the small area of collector while as the latter has the liquid heating and air heating collectors as main types based on the convection heat transfer taking place between collector surface and air or liquid (water). The efficiency of such type of collectors is increased by raising the convective heat transfer coefficient betwixt collector and fluid. Solar air heaters can be made further provident either by developing the thermal capacity of air or by advancing the heat transfer coefficient between absorber plate and air flow. The former is not possible and latter can be accomplished in two different ways viz Active method which requires external driving forces like pump work and Passive method requires special surface geometries like rough and external surfaces, fluid additives and swirl flow devices.

1. Artificial roughness concept

Convective heat exchange amidst fluid flow and absorber plate is accompanied with the creation of thermal boundary layer setting up a temperature gradient which reduces the thermal productivity of a solar air heater device. Synthetic asperity is produced using V shaped, W shaped, wire mesh, inclined, chamfered and multi V shape ribs etc. which promote turbulence thereby eschewing the formation of thermal boundary layer and improve the thermohydraulic efficiency of solar air heater Akpinar et al [1] empirically inspected the influence of using obstacles of various types in the collector plate of a SAH device. Comparison was done among various types of obstacles used based on the heat gain factor, heat loss factor and efficiency and they observed that the absorber plate with embedded obstructions was much better than that of a flat plate collector having no obstacles. Since, rate of heat transfer is a function of turbulence but creating turbulence in the fluid flow implies an increase in pump work. The problem is solved optimally using various types of ribs as roughness promoters to increase turbulence. The alterations in average friction factor and Stanton Number were provisionally examined by B N Prasad et al [2] on the absorber plate of a solar air heater holding narrow bore convexity wires. They discovered that heat transfer coefficient doubles by employing protruding strands and the pace of heat exchange is contrarily equivalent to both relative roughness height and relative roughness pitch. Sara et al. [3] researched the augmentation in efficacy of a SAH with solid and pierced rectangular blocks connected to it. The research concluded with a result indicating an energy benefit of almost 20% by employing pierced rectangular blocks. They also suggested that efficiency can be further raised by escalating the hole bore, hole area ratio and slope of pierced holes towards the collector plate. Dhananjay gupta et al. [4] explored the improvement in execution of a SAH by increasing heat exchange from collector plate providing artificial roughness which however increases the pumping power. Hence, an attempt has been made to come out with an optimal and economic solution. They observed that corresponding to every value of roughness height, effectiveness attains a peak value as mass flow rate is assorted and it diminishes with rise in e/D value. Above Reynolds number of 10000 effective
efficiency increases as insolation increases and acquires some optimum value as Reynolds number increases. The study yielded a relation and an optimal solution corresponding to a P/e value 10 and α as 60° as:

\[ R_e = 1311.2 \left(1 - \frac{e}{D}\right)^{0.281} \]

**Nikuradse [5]** thought out the outgrowth of velocity and temperature distribution for roughened surface. The contemplation unveiled that velocity profile in the turbulent flow is firmly dependent on roughness height along with flow the Reynolds number. They cultivated a relationship as follows:

\[ 0.004 < \frac{e}{D} < 0.0679 \]

\[ e^+ = \frac{e}{D} \left(\frac{f}{2}\right)^{1/2} R_e \text{ and } \]

\[ R\cdot e^+ = (2/f)^{1/2} + 2.5 \ln \left[\frac{2\epsilon}{D}\right] + 3.75 \]

**2.1 C shape ribs**

Mohitkumar G et al. [6] studied through an experiment the development in thermal and hydraulic achievement of a dual pass solar air heater coarsened with myriads of C shape ribs. They obtained a Nusselt number of 415 for a corresponding P/e value of 24, α as 90° and Re value of 15000, which yielded a friction factor of 0.031 and a thermo hydraulic performance parameter of 3.48. They concluded that double flow solar air heater is extra competent than that of single flow arrangement, and multiple C shape geometry on two sides of absorber resulted in higher heat transfer to that of dispersed C shape roughness.

![Fig.1](image)

**Fig.1.** Multiple C shaped roughened absorber; Mohitkumar G et al. [6]

The heat transfer coefficient and friction factor of rectangular ducts was calculated by Saini and Saini [7] by building the influence of arc shaped ribs on it. They discovered that on lowering the arc angle rate of convective heat exchange raised while the friction factor declined. Nusselt number and friction factor were raised by a multiple of 3.6 and 1.75 separately at a fixed relative arc angle of 0.3333 and e/D value of 0.0422. Muneesh Sethi et al [8] premeditated through an experiment the consequences of employing dimple shaped roughness components prepared in angular custom in the duct of a solar air heater. They concluded that peak value of efficiency occurs at relative roughness pitch value of 10 and angle of attack as 60°. They also reported that efficiency is a direct function of Reynolds number of flow at the expense of pump work.

**2.2 V shape ribs**

The consequences of artificial roughened absorber plate with discontinuous V down ribs on the exergetic effectiveness of a solar air heater were examined by Sukhmeet Singh et al. [9]. They observed that for a Reynolds number of less than 18000, discrete V down ribs are suitable and for a Reynolds number of greater than 18000 plain prevalent solar air heater is convenient. They observed a maximum exergetic efficiency for X T / I greater than 0.0175Km²/W at a P/e value of 8, relative gap position of 0.65, α as 60 o, relative gap width of 1.0. A model was designed by Bashariaa et al [10] to scrutinize the potency improvement of a solar air heater and cost benefit ratio using dual stream vogue as flat plate collector with permeable media and V furrow armament. They observed that the ability of solar air heater proving double pass double duct V gouge absorber increased by 4% to 15% as that of double pass flat plate collector. The outlet temperature was observed to increase from 2 °C to 8 °C. They concluded that solar air heater thermal efficiency is mainly affected as follows: Increase in discharge of air results in an increase in effectiveness of collector, decrease in outlet temperature, and a rise in pressure drop and increment is cost of solar energy. Decrease in flow depth results in an rise in collector thermal efficiency, increase in outlet temperature, and a rise in pressure drop which drives to an increment in cost of solar energy due to increase in pumping expand. A growth in collector length gives an outcome of a decrease in thermal competence and a growth in outlet temperature and pressure drop. A visible rise in collector thermal efficiency, outlet temperature and pressure drop was perceived by using a porous media.

The way heat transfer and fluid flow attributes of a rectangular duct of an absorber plate with V moulded ribs are affected were empirically researched by Ebrahim Momin et al. [11]. The research was done in the Reynolds number compass of 2500 to 18000, (e/Dh) as 0.02 – 0.034, α as 30° – 90° and a constant relative roughness pitch of 10. Owing to flow segregations, reattachments and subordinate flows resulting because of roughness a substantial improvement in Convective heat transfer and a decrease in friction factor was observed. At higher values
of e/D Nusselt number improves relatively low as that of friction factor since reattachments hardly occur. Nusselt number and friction factor were found to increase by a multiple of 2.30 and 2.83 reciprocally to that of a plain duct at α as 60°. At a e/D value of 0.034 and α as 60°, V cast ribs improve the value Nₚ by 1.14 and 2.30 times to that of oblique ribs and flat plate at a Reynolds number value of 17034.

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**Fig.2.** V shaped ribs; Ebrahim Momin et al. [11]

Ravi Kant Ravi et al. [12] experimentally analyzed the improvement in accomplishment of SAH holding disconnected multi V regulate and ribs. The research was executed at a Reynolds number range of 2000 to 20000, relative gap distance Gₖ/Lᵥ of 0.70, relative pitch ratio P/e of 10, e/D of 0.043 and relative gap width (g/e) of 1.0 relative staggered rib size (r/e) of range 1 to 2.5, relative staggered rib position of 0.2, α as 60°.

**Fig.3.** Discrete multi V shape and staggered ribs; Ravi Kant Ravi et al. [12]

### 2.3 Arc shape ribs

Vikram Bharath et al. [13] premeditated the influence of arc formed round shaped wires as turbulators in a SAH. Within the Reynolds number range of 3000 to 8000, e/Dᵥ value of 0.034, duct aspect ratio (W/B) is kept 5 and relative roughness pitch (P/e) of 10, 20, 30 and 40 is considered. The study revealed that Nusselt number, friction factor and efficiency index is maximum for double arc shaped roughness, followed by single arc roughness and minimal for plain absorber plate.

**Fig.4.** Double arc wire roughness geometry; Vikram Bharath et al. [13]

Avdhesh Sharma et al. [14] experimentally explored the influence of raggedness between collector plate and air of a double pass SAH. Ribs are attached to solar collector at four different angles of range 30° to 75°. With Reynolds number of range 4900 to 12000, e/D of range 0.022 to 0.044. The study revealed that heat transfer and friction factor attains a peak value at the e/Dᵥ value of 0.044.

Sumit Joshi et al [15] experimentally investigated the result of synthetic ruggedness provided by a combination of broken arc and staggered ribs on the performance of the collector. They observed that highest thermohydraulic performance occurs in combination of broken arc and staggered ribs. Thermohydraulic performance in highest and found to be 2.09 to 2.46 at a gap position (relative) of 0.6, P/e value of 10, and Reynolds number of range 3000 to 12000. A 33% increase in efficiency was observed for a union of broken arc and disconnected ribs in contrast to that of regular arc shaped ribs.

**Fig.5.** Broken arc and staggered ribs Sumit Joshi and L. Varshney [15]

Rajesh Kumar et al [16] premeditated the outcome of using herringbone corrugated fins engaged to below of a collector plate on the production of a SAH. They considered the effect of discharge of air, fin pitch, fin spacing ratio, flow cross section aspect ratio and solar intensity and observed that efficacy of SAH increased
from 36.2% to 56.6%. Corresponding to the values of fin pitch of 2.5 cm and fixed mass flow rate of 0.026 Kg/Sec. Herringbone corrugated fins result in better mixing of fluids and amplify the heat exchange rate due to arise in heat exchange area provided by fins. They found that collector efficiency increased by 18% when mass flow rate of air is increased from 0.016 Kg/Sec to 0.033 Kg/Sec at air temperature of 15 °C corresponding to fin pitch of 2.5 cm, mass flow rate of 0.01 Kg/Sec to 0.08 Kg/Sec. The thermohydraulic efficiency attains a maximum value of 68.965% at 0.05 Kg/Sec discharge of air and due to pressure drop beyond mass flow rate of 0.05 Kg/Sec thermohydraulic efficiency decreases to 64.4% at air flow rate of 0.08 Kg/Sec due to increase in heat transfer. On reducing fin pitch from 2.5cm to 1cm, thermal efficiency increases from 66.85 % to 71.40 %.

Mukesh Kumar Sahu et al. [17] investigated the improvement in thermohydraulic execution of a SAH with arc shaped string coarseness on the collector plate. They observed maximum thermal and effective efficiency values of 79.84% and 75.24% individually complementary to a rib height to duct hydraulic diameter ratio of 0.0422 a flow attack angle of 0.3333. They compared the results obtained to that of a customary solar air heater running under related status and observed an appreciable increase in efficiency by using an absorber plate possessing round wire rib irregularities in the cast of arc mold. They concluded that the model designed was optimal and more practical for coarsened solar air heater since, it contemplates the confines of pumping power consumption and thermal energy earn. It was observed that effectiveness raises in the Reynolds number range of 15000, after which it starts decreasing. Therefore, it is convenient to operate solar air heaters having arc mold wire coarsened absorber plate at lower Reynolds number ($R_e$ less than 15000).

N.K. Pandey at al. [18] practically studied the effect of using numerous arcs with gaps as irregularity on collector plate of a SAH. An apex increment in $N_u$ and friction factor was ascertained to be 5.85 to 4.96 separately. They observed that peak enrichment for Nusselt number comes out at $R_e$ value of 2100, gap width of 1, relative gap distance of 0.65 and relative roughness width of 5.

Fig.6. Arc shape absorber plate with wire rib roughness; Mukesh Kumar Sahu et al. [17]

Fig.7. Multiple arcs with gaps on absorber plate; N.K. Pandey at al. [18]

2.4 Transverse ribs

The proficiency in thermal and thermohydraulic ability of a SAH with a duct wherein artificial ruggedness is present in the configuration of transverse ribs in a rectangular duct was experimentally investigated by Sudhanshu Dogra [19].With duct aspect ratio as 10, Reynolds number of range 4900 to 12000, ($P/e$) of range 5 to 20, $e/D$ value of 0.044, $\alpha$ as 90, the experiment was carried out and they observed that peak effectiveness of transverse ribs exists at a $P/e$ value of 10, because of maximum reattachment points are found. Also the efficiency of a smooth plate and dual run SAH coincide at a $P/e$ value of 5.

Fig.8. Transverse ribs on absorber plate; Sudhanshu Dogra [19]

He concluded that corresponding to $P/e$ value of range 5-20, $\alpha$ as 90, and $e/D_h$ value of 0.044 efficiency increases for a particular range of Reynolds number and then declines since grade of the collected heat lowers and pump input raises.

2.5 W Shaped ribs
The enhancement in heat transfer efficiency by using cross crinkled dual run collector plate was analytically studied by Chii-Dong Ho Hsuan Chang et al. [20]. Since the heat exchange area is twofold and turbulence is also increased a significant enhancement in efficiency is observed by employing dual pass appliance with welding cross corrugated capturing plates on the contrary of practicing flat plate device. The main aim of employing cross corrugated absorber plates is to promote turbulence severity and multiply the heat transfer area. They observed that efficiency elevated by raising the recycle ratio and lowering the air mass flow rate and found to be optimal at $R = 0.5$. Deep Singh Thakur et al. [21] extended their research for 3D CFD simulations on hyperbolic rib having parabolic tip and validated them with the experimental data they had already obtained. The investigations were extended to incline V shaped and W shaped ribs to improve the thermohydraulic performance and the attacking angle was of the range 30° to 90°. Thermohydraulic efficiency was found to be best for roughness height of $e$ as 1mm, pitch as 10mm and $R_e$ as 10000 to that of rectangular, triangular and semicircular ribs. V, W and inclined rib configurations were tested, four rib angles of 30°, 45°, 60° and 90°. Due to formation of eddies because of flow separations and secondary flow of eddies along the ribs. Thermohydraulic performance was found to increase at corresponding increasing values of angle of attack. They deduced that V formed rib configurations of hyperbolic rib shape having parabolic tip gave better outcome corresponding to $e = 1$mm, $p = 10$mm, $R_e = 60000$ and angle of attack as 60°.

The influence of using W forged ribs as coarseness constituents on the heat transfer and friction factor of a SAH were elaborated through an experiment by Atul Lanjewar et al. [22]. The contemplation was executed at a breadth to elevation ratio of 8, $P/e$ value of 10, $e/D_h$ of range 0.018 to 0.03375 and attacking angle of range 30 to 70 degrees. The study revealed that maximum thermohydraulic efficiency occurs at an $e/D$ value of 0.03375, attack angle of 60° and Reynolds number of 14000.

![Fig.9. W shaped ribs; Atul Lanjewar et al. [22]](image)

### 2.6 Heat storage in a solar air heater

The result of filling up the storage unit with a commercial grade paraffin wax on the achievement of a SAH was practically calculated by W Smolec et al [23]. They observed that the efficacy of SAH is considerably improved by employing the heat storage unit. The efficiencies of solar air heaters without heat storage units, with heat storage units filled with wax, and the solar air heater with storage units filled with wax and thin aluminum strip matrix was found to be 0.40, 0.42 and 0.44 respectively. Approximately a 10% increase in efficiency was observed. The solar air heater with heat storage unit was found to deliver warm air (5°C greater than ambient temperature) continuously for one hour after radiation has ceased.

Guruprasad et al. [24] scrutinized the features of solar thermal energy depository substances for use in solar air heaters to magnify the effectiveness of same. They searched for an optimal substance for use in solar thermal energy storage devices to be economically convenient and increase the efficiency of storage devices. High, medium and low temperatures are the three main types of thermal energy storage materials observed. The first one includes inorganic substances like nitrate salts, and the latter two encrypt the materials like commercial paraffin wax. In addition to increasing thermal conductivity of materials cost effective manufacturing technologies are also being explored. Due to their high volumetric energy storage capacity, thermo chemical materials are a point of main concern in future. Abhishekh saxena et al [25] learned the outcome of practicing Granular Carbon for long term heat storage of a SAH for exploring the uses of such devices beyond conventional practices of drying of crops, seasoning of timber, and space warming to industrial diligence and thermal power plants. They observed that the device performed quit well for various configurations in both natural and forced convection.

### 1.7 Recycling of fluid flow in SAH

The result of introducing a collector plate to bisect a flat plate convey into two sub channels on the proficiency of a SAH was provisionally examined by Chii-Dong Ho et al. [26]. Wire mesh packed devices were used to improve the heat transfer efficiency. An ample progress in heat transfer was observed by executing wire entanglement compact dual pass procedure beneath the absorber plate with forced convection. At the maximum discharge of...
0.0214 Kg/Sec and $T_{in}$ as 30 °C, the value of collector efficiency was observed to be 0.52. Ho-Ming et al [27] elaborated the ascendancy of internal recycle on the competence of a SAH taking into account the issue of recycle ratio too. They detected assessable betterment in efficacy of a SAH by working out internal recycle. They also recommended that while internal recycle raises fluid velocity but it also declines the temperature difference.

The amendment in heat exchange efficacy of a SAH by bisecting the flow stream of a flat plate by inserting a device in absorber plate was studied through an experiment by C.D. Ho et al. [28]. The two parts of the channel having fins were engaged by baffles and outside recycling was done at the ends. An indicative increment in heat transfer efficiency was detected by adopting baffled double pass process. Baffled solar air heater gave larger heat exchange area and higher turbulence hence an enrichment in heat exchange was achieved. An optimal solution was concluded considering the fact that higher energy dissipation takes place at higher discharge and recycle ratio, which otherwise are convenient for improving absorber plate effectiveness.

![Baffled solar air heater](image1.png)

**Fig.10.** Baffled solar air heater; C.D. Ho et al. [28]

The amendment in collector proficiency of a double pass channel plain prevalent SAH by employing a collector plate with aluminum cans embedded in it was explored by Filiz Ozgen et al. [29] through an experiment, which leads to an increase in fluid rapidity and heat exchange. Three types of absorber plates were designed and tested viz absorber plate with zig-zag staggered cans, absorber plate with ordered cans and absorber plate without any cans. They observed that absorber plate in which cans was placed in zig-zag manner gave maximum efficiency.

![Aluminum cans used in absorber plate](image2.png)

**Fig.11.** Aluminum cans used in absorber plate; Filiz Ozgen et al. [29]

The contemplation gave a conclusion that the collector with random embedded aluminum cans is more efficient since air passes past and beneath absorber plate at once.

### 3. Conclusion

The literature study reveals that large amount of experimental work is done on heat transfer of roughened flow passages. From this work, swirl producers like ribs, hinders and clogs, blockages and winglets are considerably to use. Turbulence boosters augment the fluid mingling and obstruct the evolution of thermal boundary layer. The sturdy thwarts amplify the heat transfer following an eminent rise in friction factor. Considerable elaboration in heat exchange can be attained with less retribution of abrasion. A number of alterations have been put forth for heat transfer and friction factor for solar air heater ducts with synthetic ruggedness of diverse shapes, which can be applied to anticipate the overall achievement the said devices. The literature survey also revealed that Nusselt Number and Friction factor are functions of $Re$, $e/D$, $P/e$, Rib shape and Duct shape. The optimum value of $P/e$ is advised to be kept nearer to 10 since, reattachments don’t take place at lower values of $P/e$ and higher values of $P/e$ imply higher friction factor. The roughness height should be slightly higher than transition sub layer thickness. Also the use of inclined ribs is recommended to avoid formation of stagnant vortices and thereby enhancing the efficiency of solar air heater.

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