A Descriptive Review to Access the Most Suitable Rib’s Configuration of Roughness for the Maximum Performance of Solar Air Heater

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Abstract: Solar air heater is considered to be the most popular and widely used solar thermal system. Solar air heater (SAH) can be used in many applications, ranging from domestic to industrial purposes. However, it seems that the viability of SAH is not feasible due to the following two reasons: (i) the low convective heat transfer coefficient at the absorber plate is the reason that causes a low heat transfer rate to the flowing air, and (ii) the high temperature of the absorber plate insists on high heat losses, thus, reducing the thermal efficiency. The convective coefficient can be augmented by placing turbulators/roughness on the absorber plate, which induces turbulence in the flow passage near the absorber plate by disrupting and destabilizing the laminar sublayer. This comprehensive review has been presented to summarize the studies on artificial roughness/turbulators geometries to enhance the heat transfer rate. Various rib configurations (such as grits, grooves, blockages, baffles, winglets, protrusions, twisted taps, dimples, and mesh wires) and distinct arrangements of rib roughness (such as inclined, transverse, V shape, with gap) have been reviewed to present heat transfer and friction characteristics. Additionally, thermal efficiency and thermohydraulic efficiency (in terms of net effective efficiency) of various artificial roughnesses and rib configurations are presented under distinct operating conditions for comparing purposes. This comparative study has been presented to assess the most desirable ribs and their configurations. On the basis of net effective efficiency, a multiarc rib with gaps is found to be the best configuration among all and have the highest thermal and net effective efficiency of around 79%.

Keywords: roughness; performance; solar air heater; friction factor; Nusselt number; augmentation

1. Introduction

The consumption and demand for energy increased globally due to the drastic rise in industrialization, population, and economic growth of nations. In this respect, the researchers developed various energy-saving techniques as a new source of energy in the field of energy production and saving; various conventional fossil fuels, such as petroleum products, crude oil, coal, and nuclear fuel, are used for energy production, which are very exhaustible and also have adversely affected the nature and surrounding environment. However, many investigators have performed a lot of work to minimize the effect of fossil fuel emission, such as NOx and CO2, in the environment. Solar energy is an indigenous and most promising energy source available worldwide. Among all available renewable sources of energy, solar energy is an infinite source of energy and also has the largest potential to fulfill the energy demand on earth. Solar energy can be converted into heat energy by using solar collector devices. Solar air heater (SAH) is the best example of these solar collector devices. The SAH heats the flowing air by absorbing direct and diffused solar radiation from low to moderate temperature for distinct applications, such as building...
heating, drying of vegetables, drying of fruits, timber seasoning, crop drying, space heating, and many other industrial and domestic purposes. It is free from problems related to freezing and corrosion. SAH can also be used to increase the efficiency and performance of a conventional drying system by integrating these systems in many applications, such as conveyor and fluidized bed drying systems.

SAHs are widely used in the world for heating purposes because they are very simple in design, economical, and almost maintenance-free. The main components are the collector plate, transparent cover of high transmissivity, back insulations, side edges, and blower/fan, as shown in Figure 1. The SAH has poor performance due to the low convective heat transfer coefficient of the absorber plate and high heat losses from the top glass cover. Due to the development of the laminar sublayer at the absorber plate because of the thermal resistance generated near the plate retards’ heat transfer. The convective coefficient can be augmented by using turbulators, which induce turbulence in the duct near the absorber plate by disrupting and destabilizing the laminar sublayer. The viscous sub-layer can be disrupted by using irregular-shape obstacles, called artificial roughness, in distinct form of grits, groove, baffles, ribs, winglet, protrusions, twisted taps, dimples, perforation, mesh wire, and so on [1]. The roughness may be in a square, rectangular, triangular, conical, spherical, or chamfered shape or in a hybrid shape. The turbulence promoters also increase friction losses, which leads to higher power consumption in the pumping of air, which is not desirable. Therefore, the turbulence zone should be within the region of the viscous sublayer.

![Figure 1. Component of SAH.](image)

The objective of this review paper is to summarize the works carried out for the performance enfacement of SAH, exploiting the artificial roughness/turbulators of different configurations. Additionally, a performance analysis of various rib configurations is presented to assess the best rib configuration. This study will be helpful to readers who are working in heat transfer enhancement. In the following subsection, the concept of artificial roughness and their corresponding effect are discussed. Additionally, the performance of SAH having artificial roughness is discussed in detail.
2. Performance of SAH

2.1. Heat Transfer Performance

It can be evaluated with the help of an equation proposed by Bliss [2], which is given as:

\[ q_u = F_R \{ I(\tau \alpha) - U_o(T_i - T_a) \} \] (1)

Further, the efficiency of a SAH is given as:

\[ \eta_{th} = F_R \left[ \left( \tau \alpha - U_o \frac{(T_f - T_a)}{I} \right) \right] \] (2)

2.2. Hydraulic Performance

It is totally concerned with pressure drop, which leads to excessive power consumption to run the blower or fan. The pressure drop inside the duct in relation to the friction factor is given as:

\[ \Delta P = \frac{2fL\rho V^2}{D_h} \] (3)

The overall performance should be evaluated with the help of various considerations of thermohydraulic performance. The thermohydraulic performance is helpful in the selection of a parameter and solar collector design. The collector should transfer a maximum amount of heat energy with minimum power consumption in the blower. The parameter for augmentation in the thermal performance of a rough duct in comparison with a smooth duct in terms of friction factor and \( Nu \) was developed by Lewis et al. [3], called thermohydraulic performance parameter (\( \eta \)), which is given below.

\[ \eta = \left[ \frac{(Nu/Nu_s)}{(f/f_s)^{1/3}} \right] \] (4)

3. Historical Background of Conceptualization of Artificial Roughness in SAH

The SAH is a simple, compact, and economical thermal heating system that has wide applications in so many fields, such as the domestic, industrial, automobile, and agriculture fields. Solar radiations are converted into thermal energy with the help of an absorber plate in the SAH. The flat plate collectors are mainly used in the SAH for distinct heating applications in a wide span. The thermal performance of a SAH is weaker due to a small value of the convection coefficient. This is due to the development of a laminar sublayer adjacent to the absorber plate, which offers thermal resistance to the convection. Therefore, it is imperative to augment the performance of the SAH by adopting a desirable technique of heat transfer augmentation. The convective coefficient can be augmented by installing turbulators on the wall of the duct, which induces turbulence in the flow passage near the absorber plate by disrupting and destabilizing the laminar sublayer. The artificial roughness revives the fluid flow pattern adjacent to the absorber plate in the region of a viscous sublayer. The artificial roughness may be in any suitable shape, such as square, rectangular, triangular, conical, spherical, chamfered, or hybrid shape. The roughness geometries used by many researchers are grits, grooves, blockages, baffles, winglets, protrusions, twisted taps, dimples, mesh wires and so on. Alam et al. [1] reviewed distinct arrangements of rib roughness that have been investigated previously, such as V-rib, W-shape rib, chamfered rib, rib with grooves, staggered rib, transverse rib, and discrete rib. The effect of flow due the various rib arrangements is discussed in detail.

The separation and reattachment of flow occur due to roughness in between consecutive roughnesses, which leads to an increment in local wall turbulence, thereby enhancing the convection coefficient. Okamoto et al. [4] analyzed that the value of a local convective coefficient is maximum at the reattachment point as the turbulence intensity is highest just downstream this point. Sparrow et al. [5] showed both experimentally and numerically that
the point of reattachment of the flow and position of the maximum convection coefficient is quite close to each other. Cortes and Piacentini [6] developed a performance assessment parameter of the SAH with the help of a numerical model called effective efficiency. They also showed that the effective efficiency of a collector may be enhanced with the help of perturbations. The obstacles also increase air pumping power requirements. Nikuradse [7] studied the turbulent flow of fluids with a distinct degree of relative roughness and developed the temperature and velocity distributions of a sand-grain-roughened pipe for a large span of roughness Re ($e^+$).

\[ e^+ = \frac{e}{D} \sqrt{\frac{f}{2} \text{Re}} \]  

(5)

Roughness Re is a parameter that combines both the roughness height and Re. Nikuradse [7] identified three regions of fluid flow based on variation in $f$ for a wide span of $e^+$, which are shown in Figure 2.

In the hydrodynamically smooth flow region, the value of $f$ for a small range of roughness Re ($5 > e^+ > 0$) is the same for a smooth and rough pipe, and the roughness exists entirely within the laminar sublayer. In the transitionally rough flow region, the magnitude of $f$ increases with the rise in roughness Re as the value of $f$ is a function of roughness Re in this range ($70 > e^+ > 5$). The thickness of the laminar sublayer is the same as the height of the roughness element in this region. Additionally, in the fully rough flow region, the value of $f$ is not depending on the roughness Re in this range ($e^+ > 70$). The friction factor follows the quadratic law of resistance. The height of the roughness extends through the laminar sublayer.

Dipprey and Sabersky [8] developed a wall similarity law that is applicable for both smooth and rough tubes. Webb et al. [9] developed a correlation of heat transfer and $f$ for a repeated rib roughness in case of turbulent flow within the tube. The correlation of heat transfer is based on heat momentum transfer analogy as previously used by Dipprey and Sabersky [8], and friction correlations are based on the wall similarity law as previously used by Nikuradse [7] in the case of the sand grain type of artificial roughness.

\[ g(e^+, Pr) = u e^+ + \frac{(f/2St - 1)}{\sqrt{f/2}} \]  

(6)

The ability of the heat transfer of an artificially rough surface is shown by $g(e^+, Pr)$.

Webb et al. [10] further extended the range of validity of these correlations and proposed that the justified value of $e^+$ is greater than 35. Vilemas and Simonis [11] experimentally investigated friction and convective heat transfer in inner rough tubes for Re numbers 5000 to 500,000. They also developed correlations for friction and heat transfer as given below;

For a fully rough flow condition with rectangular roughness in annular channels:

\[ N_t = 0.029\text{Re}^{0.84}\text{Pr}^{0.6}\psi^n \]  

(7)

For a partially rough flow condition with rectangular roughness in annular channels at $e/D_e \geq 0.0025$:

\[ N_t = (0.0053 - 0.14e/D_e)\text{Re}^{0.95+7e/D_e}\text{Pr}^{0.6}\psi^n \]  

(8)

where

\[ n = -(0.29 + 0.035\sqrt{e/D_e})\text{Re}^{-24e/D_e}(1 - e^{-0.16x/D_e}) \]

The friction factor for channels with rectangular roughness:

\[ f = (0.053 + 1.85e/D_e)\text{Re}^{-0.07} \]  

(9)

Han et al. [12] experimentally investigated the effect of a distinct rib roughness of various shapes, sizes, and cross sections on heat transfer and $f$. Both St and $f$ have the best
value corresponding to $p/e = 10$. The heat transfer and $f$ correlation are developed based on heat momentum transfer analogy and the wall similarity law, as previously used by Dipprey and Sabersky [8]. They studied four angles of attack between rib roughness and mainstream flow as $20^\circ$, $45^\circ$, $75^\circ$, and $90^\circ$. The value of $\alpha = 45^\circ$ has superior convective performance in comparison with others. The correlation for the friction factor:

$$
Re^+ = 4.9(e^+ / 35)^a / \left[ (\varphi / 90^\circ)^{0.35} (\alpha / 45)^{0.57} \left( \frac{10}{p/e} \right)^b \right] \tag{10}
$$

where,

$a = -0.4$ when $e^+ < 35$ and $a = 0$ when $e^+ \geq 35$

$b = -0.13$ when $p/e < 10$ and $b = 0.53(\alpha / 90^\circ)^{0.71}$ when $p/e \geq 10$

Figure 2. Flow patterns due to distinct relative rib height [13].

The correlation for heat transfer:

$$
Qe^+ = 10(e^+ / 35)^i / |\alpha / 45^\circ|^j \tag{11}
$$

where,

$i = 0$ when $e^+ < 35$ and $i = 0.28$ when $e^+ \geq 35$

$j = 0.5$ when $\alpha < 45^\circ$ and $j = -0.45$ when $\alpha \geq 45^\circ$

Prasad and Saini [13] experimentally studied that for specific values of $p/e$ and $e/D_h$, a geometrically similar roughness has the same effect on the convection coefficient and $f$. The convective coefficient decreases, and the value of $f$ increases as $e/D_h$ increases. Gupta et al. [14] experimentally investigated that as the relative height of artificial roughness escalates, the optimum flow rate shifts to a lower value. They studied that the Stanton number increases up to $Re = 12,000$ and decreases after further increment in the value of $Re$.

4. Effect of Distinct Roughness Parameters

The geometrical parameter of roughness has significant effects on the performance of the SAH. Artificial roughness can be in a distinct shape and size and also in different
orientations. According to Lewis [3], the heat transfer and momentum loss function of roughness depend on various parameters of artificial roughness and duct.

\[
g = g(e^+, Pr, p/e, e/b, C_d, e/D_h, c/e, a, shape, duct cross – section) \quad (12)
\]

\[
R = R(e^+, p/e, C_d, e/b, e/D_h, c/e, a, shape, duct cross – section) \quad (13)
\]

The effects of distinct types of rib roughness and various parameters investigated by various researchers are discussed below.

4.1. Effect of Relative Rib Height

The performance of a roughened duct remarkably depends on \( e/D_h \). The value of the friction factor increases, and \( Nu \) decreases with the increase in \( e/D_h \). On the other hand, the rate of increase in average \( Nu \) decreases with an increase in \( e/D_h \). Prasad and Saini [13] analyzed the effects of \( e/D_h \) on the thermohydraulic performance of the SAH. The reattachment occurs only for a small value of \( e/D_h \) and does not take place for higher values. The separation and reattachment of flow produced maximum convective heat transfer within a laminar sublayer region. Reattachment occurs only for a small value of \( e/D_h \) (Figure 2). Amel Boulemtafes-Boukadoum et al. [15] investigated the performance of the SAH with the help of transverse ribs and also distributed ribs on heat transfer in the upward SAH. They used nondimensional heights of ribs as 66 and 50. The values of \( e/D_h \) at which the highest rate of heat transfer was achieved for distinct roughness geometries are shown in Table 1.

Table 1. Values of \( e/D_h \) at which the highest rate of heat transfer for distinct roughness geometries is investigated in the SAH duct.

| S. No. | Researchers | Geometry of Artificial Roughness | Value of \( e/D_h \) |
|-------|-------------|----------------------------------|---------------------|
| 1     | Prasad and Saini [13] | Continuous transverse rib | 0.0333 |
| 2     | Singh et al. [16] | Nonuniform saw-tooth-shaped rib | 0.043 |
| 3     | Aharwal et al. [17] | Inclined rib with gap | 0.0377 |
| 4     | Singh et al. [18,19] | V-shaped with gap | 0.043 |
| 5     | Sabu and Bhagoria [20] | Broken transverse rib | 0.0338 |
| 6     | Yadav and Bhagoria [21] | Triangular-shaped rib | 0.042 |
| 7     | Yadav and Bhagoria [22] | Square-shaped rib | 0.042 |
| 8     | Gupta et al. [23] | Continuous inclined rib | 0.033 |
| 9     | Momin et al. [24] | V-shaped continuous rib | 0.034 |
| 10    | Maithani and Saini [25] | V-shaped rib with symmetrical gap | 0.043 |
| 11    | Deo et al. [26] | Multi-V-shaped rib with gap combined with staggered rib | 0.044 |
| 12    | Patil et al. [27] | V-rib with gaps combined with staggered rib | 0.0433 |
| 13    | Hans et al. [28] | Continuous multi-V-rib | 0.043 |
| 14    | Kumar et al. [29] | Multi-V-rib with gap | 0.043 |
| 15    | Saini and Saini [30] | Arc rib | 0.0422 |
| 16    | Sethi et al. [31] | Dimple rib in arc pattern | 0.036 |
| 17    | Yadav et al. [32] | Dimple rib in arc pattern | 0.030 |
| 18    | Hans et al. [33] | Broken arc rib | 0.043 |
| 19    | Pandey et al. [34] | Multiarc rib with gaps | 0.044 |
| 20    | Singh et al. [35] | Multiarc rib | 0.045 |
| 21    | Lanjewar et al. [36,37] | Continuous W-rib | 0.03575 |
| 22    | Kumar et al. [38] | Discrete W-rib | 0.03575 |
| 23    | Gawande et al. [39] | L-shaped rib | 0.042 |
| 24    | Kumar et al. [40] | S-shaped rib | 0.043 |
| 25    | Bhushan and Singh [41] | Protrusion roughness | 0.030 |
| 26    | Singh I and Singh S [42] | Transverse rib with square wave profile | 0.043 |
| 27    | Saini and Saini [43] | Expanded metal mesh | 0.039 |
| 28    | Karmare and Tikekar [44] | Metal grit | 0.044 |

4.2. Effect of Relative Rib Pitch

The friction factor and \( Nu \) enhance with the increase in \( p/e \). For a high rate of heat transfer, \( p/e \) should lie between 8 and 10. Prasad and Saini [13] experimentally investigated the effects of \( p/e \) on the thermohydraulic performance of the SAH by using the same \( e/D_h \) and varying the value of pitch, as shown in Figure 3. The reattachment occurs only when
the value of $p/e$ is more than 8. The convection coefficient has the highest values near the reattachment point. The values of $p/e$ at which highest rate of heat transfer was achieved for distinct roughness geometries are shown in Table 2.

![Figure 3. Flow pattern due to distinct $p/e$ [13].](image_url)

**Table 2.** Values of $p/e$ at which the highest rate of heat transfer for distinct roughness geometries is investigated in the SAH duct.

| S. No. | Investigators | Type of Roughness | $p/e$ |
|--------|---------------|-------------------|-------|
| 1      | Prasad and Saini [13] | Continuous transverse rib | 10    |
| 2      | Singh et al. [16] | Nonuniform saw-tooth-shaped rib | 8     |
| 3      | Aharwal et al. [17] | Inclined rib with gap | 10    |
| 4      | Singh et al. [18,19] | V-shaped with gap | 8     |
| 5      | Yadav and Bhagoria [21] | Triangular-shaped rib | 7.14  |
| 6      | Yadav and Bhagoria [22] | Square-shaped rib | 7.14  |
| 8      | Gupta et al. [23] | Continuous inclined rib | 10    |
| 9      | Momin et al. [24] | V-shaped continuous rib | 10    |
| 10     | Karwa [45] | Transverse rib | 10    |
| 11     | Maithani and Saini [25] | V-shaped rib with symmetrical gap | 10    |
| 12     | Deo et al. [26] | Multi-V-shaped rib with gap combined with staggered rib | 12    |
| 13     | Patil et al. [27] | V-shaped rib with gap combined with staggered rib | 10    |
| 14     | Saini and Verma [46] | Dimple-shaped | 10    |
| 15     | Hans et al. [28] | Continuous multi-V-rib | 8     |
| 16     | Kumar et al. [29] | Multi-V-ribs with gap | 10    |
| 17     | Saini and Saini [30] | Arc ribs | 10    |
| 18     | Sethi et al. [31] | Dimple rib in arc pattern | 10    |
| 19     | Yadav et al. [32] | Dimple rib in arc pattern | 12    |
| 20     | Hans et al. [33] | Brocken arc rib | 8     |
| 21     | Pandey et al. [34] | Multiarc rib with gaps | 8     |
| 22     | Singh et al. [35] | Multiarc rib | 8     |
| 23     | Lanjewar et al. [36,37] | Continuous W-rib | 10    |
| 24     | Kumar et al. [38] | Discrete W-rib | 10    |
| 25     | Gawande et al. [39] | L-shaped rib | 7.14  |
| 26     | Kumar et al. [40] | S-shaped rib | 8     |
| 27     | Bhagoria et al. [47] | Wedge-shaped rib | 7.57  |
| 28     | Karmare and Tikekar [44] | Metal grit | 17.5  |
| 29     | Layek et al. [48] | Chamfered rib combined with groove | 6     |
4.3. Effect of the Cross Section of Rib

The rib cross section has a remarkable impact on thermohydraulic characteristics. Singh et al. [16] studied the performance of the SAH with the help of 3D computational fluid dynamics (CFD) investigations. They studied a roughened duct with an uneven cross-section transvers rib of saw tooth type. This type of roughness shows a higher convection coefficient at Re more than 7000 due to disruption in recirculation. The variation in Nusselt number of surface in comparison with other cross sections w.r.t. to Re is shown in Figure 4. Experiments have been carried to study the thermal performance of five types of ribs that have different cross sections, shapes, and sizes [49]. The sharp cross-sectional rib, such as pentagonal, wedge, square, rectangular, triangular, or trapezoidal, produced radial fluctuating components in the turbulence region. The level of turbulence and reattachment profile is different for different cross sections. The circular or arc-type cross section produces a low level of turbulence because of continuous surface and low-pressure drop.

![Figure 4. Nu vs. Re for various cross sections of rib roughness [16].](image)

4.4. Effect of Angle of Attack

The value of $\alpha$ has a remarkable impact on the performance of the SAH. The inclined rib induces a secondary flow in the mainstream along the roughness. Dipprey and Sabersky [8] studied four angles of attack between rib roughness with respect to the stream of flow as $20^\circ$, $45^\circ$, $75^\circ$, and $90^\circ$. Among these, $\alpha = 45^\circ$ has superior thermal performance in comparison with others. Taslim et al. [50] experimentally studied the effect of inclined ribs (Figure 5) on the performance of the SAH. The inclined ribs induce vortices just after the application of roughness at the leading edge. After that, it advances along the span of the rib. These vortices increase the turbulence, which results in a high heat transfer rate. They also reported that $45^\circ$ ribs have the highest thermal performance. A high convection coefficient region occurs at the leading edge, and a low region of convection occurs at the trailing edge. The values of $\alpha$ at which the highest rate of heat transfer was achieved for distinct roughness geometries are shown in Table 3.

![Figure 5. Vortices due to 45° angled rib [51].](image)
4.5. Effect of Relative Gaps in Continuous Rib

The performance of the SAH also depends on the gaps between the continuous ribs. The large gap between the continuous ribs retards the flow, and the small gap has less space to flow. The gaps between the continuous ribs, released a secondary flow and mixed with mainstream. The generated vortices and flow pattern of these inclined and discrete ribs are shown in Figure 6. Sahu and Gandhi [52] also numerically studied the thermohydraulic performance of inclined continuous ribs with a gap in the SAH duct. Aharwal et al. [53] further investigated inclined ribs with a c/e of 1.0. This arrangement of roughness shows the highest thermal performance.

4.6. Effect of Reynolds Number

The upstream artificial roughness enhances the turbulence level by reducing the reattachment length of the flow. This is due to a decrement in the momentum of flow and mass flux due to which the recirculation zone behind the roughness decreases. The reattachment region shows the highest heat transfer rate in comparison with the region before the reattachment point. Therefore, the reattachment distance from the roughness element decreases as Re increases for a particular boundary layer thickness to a roughness height ratio. The reattachment length varies from 1.4 e to 4 e. The reattachment length strongly depends upon Re up to 8500 and weakly depends on Re above 8500 [55,56].

5. Artificial Roughness/Turbulators

Many researchers have investigated distinct types of artificial roughness arrangements, which have remarkable effects on the performance of the SAH. The distinct artificial arrangement used in different SAH ducts are discussed as follows:

5.1. Transverse Ribs

These ribs disrupt the laminar sublayer and divert the secondary flow towards the sidewall of the duct. Various researchers have studied numerically and experimentally the effect of transverse ribs on the thermohydraulic performance for different rib arrangements. Prasad and Saini [13] studied the effect of a transverse rib on the performance of a SAH for Re ranging from 5000 to 50,000. They used a wire of small diameter as roughness. They reported that as the value of $e/D_h$ increases, convective heat transfer goes on decreasing, and the value of $f$ increases. The $f$ and $Nu$ are augmented 4.25 and 2.38 times, respectively, in comparison with a smooth duct. Gupta et al. [14] also experimentally investigated the thermohydraulic performance at $p/e = 10$ by using transverse roughness at Re varying from 3000 to 18,000; the aspect ratio of the duct varied from 6.8 to 11.5, and $e/D_h = 0.018$ to 0.052. The St number increases up to Re = 12,000 and decreases for a higher value of Re. Singh et. al. [57] studied the effect of broken transverse ribs on the performance of the SAH for Re ranging from 3000 to 18,000. They used rib parameters of $e/D_h$ equal to 0.043 and $p/e$ equal to 10. The maximum THPP is 2.10 at Re of 15,000. The highest value of thermal efficiency for smooth ducts and with multiple broken ribs is 44.26% and 72.25%, respectively.
respectively. Additionally, the maximum effective efficiency is 44.25% and 69.15%, respectively. Prasad and Mullick [58] studied the effect of a small-diameter wire as roughness in transverse direction to the direction of the flow. The protruding wires as a roughness element augment the convection coefficient. The collector efficiency factor increases from 0.68 to 0.72 corresponding to the enhancement in thermohydraulic performance equal to 14% at Re = 40,000.

Karwa et al. [59] studied the effect of repeated chamfered ribs (Figure 7) on the performance of a SAH at Re ranging from 3750 to 16,350. They applied artificial roughness in transverse direction to the flow from one sidewall to the other end of the duct. Nu and the friction factor enhanced from 50% to 120% and 80% to 290%, respectively. The thermal efficiency of the SAH increased from 10% to 40%. Verma and Prasad [60] experimentally investigated the thermohydraulic performance of a SAH by using small-diameter wires as roughness elements in the transverse direction with p/e values varying from 10 to 40 and e/Dh values from 0.01 to 0.03 at Re values of 5000 to 20,000. The value of e+ varied from 8 to 42. They obtained an optimum performance of 71% at e+ value of 24.

Sahu and Bhagoria [20] studied the effects of a transverse broken rib (Figure 8) on the thermohydraulic performance of the SAH with e/Dh = 0.0338 and a p/e range of 10–30. The height of the roughness was 15 mm, and values of Re = 3000–12,000. They reported that the value of Nu is the maximum for p/e = 20 and also studied that the smooth duct shows better thermal performance at low Re (i.e., below 5000 in comparison with a roughened duct). The heat transfer was augmented in the range of 1.25 to 1.40.

Figure 7. Chamfered transverse rib roughness [61].

Figure 8. Transverse broken ribs [54].

Behura et al. [62] investigated the effects of a three-side transverse type of roughness on the thermohydraulic performance of the SAH by using a wire with 20, 22, and 24 SWG dimensions at Re ranging from 5000 to 13,000. The heat transfer factor increased by 0.3% to 0.4%.
5.2. Inclined Ribs

Various researchers numerically and experimentally studied the effect of an inclined rib on thermohydraulic performance with respect to the flow of air and the arrangement of a rib attachment. Gupta et al. [23] analyzed the effect of incline repeated ribs of circular cross section (Figure 9) on the performance of the SAH. The value of $p/e$ was fixed at 10, Re ranged from 3000 to 19,000, and the value of $e/D_h$ ranged from 0.023 to 0.050. The thermal efficiency was enhanced 1.16 to 1.25 times over the smooth duct. Aharwal et al. [63] studied the effect of a square cross-section inclined repeated rib with gaps (Figure 10) on the SAH for the value of $e/D_h$ equal to 0.0337, $\alpha$ equal to 60$^\circ$, and $p/e$ equal to 10 at Re ranging from 3000 to 18,000. The gap in inclined ribs generates a secondary flow, which creates extra turbulence and thermal performance. The friction factor and $Nu$ were augmented up to 2.87 and 2.59 times, respectively, over the smooth duct. Further, Aharwal et al. [17] analyzed the performance by varying different parameters, such as $e/D_h$, $\alpha$, $p/e$, and the relative gap position. The $e/D_h$, $p/e$, and $\alpha$ varied from 4 to 10, 0.018 to 0.0337, and 30$^\circ$ to 90$^\circ$, respectively. The $f$ and $Nu$ were augmented up to 3.6 and 2.83 times, respectively, over the smooth duct for $e/D_h = 0.037$, gap position = 0.25, and a gap width of 1. The flow over inclined ribs is shown in Figure 11. Lu and Jiang [64] experimentally investigated the effect of an inclined rib at $\alpha = 45^\circ$ on the performance of the SAH in a rectangular duct. Further, they numerically investigated the thermohydraulic performance of an inclined rib with inclination angles as 0$^\circ$, 10$^\circ$, 20$^\circ$, 30$^\circ$, 45$^\circ$, 60$^\circ$, and 90$^\circ$. The 60$^\circ$ inclined rib showed the highest convective heat transfer, and the 20$^\circ$ inclined rib showed the best thermohydraulic performance.

![Figure 9. Inclined repeated ribs [65].](image)

![Figure 10. Inclined continuous repeated ribs with a gap [17].](image)
5.3. V-Shaped Ribs

Various researchers have experimentally and numerically investigated the effect of a V-shaped rib on thermohydraulic performance with respect to the flow and distinct attachment arrangement of roughness. Momin et al. [24] studied the effect of various geometric parameters of V-shaped artificial rib roughness (Figure 12) on the thermohydraulic performance of a rectangular duct at Re ranging from 2500 to 18,000. The $p/e$ remained fixed at 10, $e/Dh$ varied from 0.02 to 0.034, and $\alpha$ varied from 30 to 90°. The friction factor and $Nu$ decreased and increased, respectively, with an increase in Re. The highest augmentation in the friction factor and $Nu$ was found at $\alpha = 60°$ at 2.83 and 2.30 times, respectively, in comparison with a smooth duct. V-shape ribs are advantageous in comparison with inclined ribs. They show a value of $Nu$ 1.14 times more at a Re value of 17,034 in comparison with inclined ribs.

Singh et al. [19,67] analyzed the performance of a roughened duct by using a V-shaped down discrete rib (Figure 13) type of roughness. The experimental parameters Re, $e/Dh$, $p/e$, $\alpha$, $g/e$, and $d/x$ varied in the range of 3000–15,000, 4–12, 0.015–0.043, 30°–75°, 0.5–2.0, and 0.20–0.80, respectively. The highest augmentation in friction factor $Nu$ was 3.11 and 3.04 times over the smooth duct, which occurred at $\alpha$ equal to 60°. The highest value of THPP was 2.06. The effective efficiency was enhanced up to 91% as that of the SAH with a smooth duct. According to Alam et al. [51], the geometrical parameter of roughness has significant effects on the thermohydraulic performance of the SAH. Singh et al. [68] further investigated the effect of a V-shaped down rib with a gap on the performance of the SAH. The highest values of $f$ and $Nu$ were achieved at $p/e = 8$. The value of THPP ranged from 1.27 to 1.93. Karwa et al. [45,69] analyzed the effect of a repeated rib in a rectangular cross-section V-discontinuous and V-discrete arrangement. The relative roughness length and $\alpha$ varied from 3 to 6 and 45° to 60°, respectively. The discrete V-shaped ribs with $\alpha = 60°$ showed better performance in comparison with discrete V-shaped ribs with $\alpha = 45°$. The V-down arrangement of ribs showed better performance in comparison with the V-up pattern. Hans et al. [28] also studied the effect of a continuous multi-V-rib shown in Figure 14. Maithani and Saini [25] analyzed effect of a V-shaped rib with multiple symmetrical gaps (Figure 15) on the thermohydraulic performance of the SAH. The thermohydraulic performance of the SAH was studied for Re 18,000, whereas $p/e$ varied from 6 to 12 with
symmetrical gaps in one limb of V-rib varying from 1–5, g/e varied from 1–5, and \( \alpha \) varied from 30° to 75°, however, \( e/D_h \) is kept fixed at 0.043. The thermohydraulic performance of the SAH strongly depends on the number of symmetrical gaps and g/e in the limbs. The \( f \) and \( Nu \) was augmented 3.67 and 3.6 times, respectively. The highest value of \( Nu \) is achieved at three symmetrical gaps and further, incremented in the number of gaps, degrading the thermal performance. The value of \( Nu \) increased up to g/e equal to 4 and thereafter decreased. Deo et al. [26] analyzed the effect of a multigap V-shaped down-rib combined with a staggered rib (Figure 16) on the performance of the SAH.

![Figure 13. V-down discrete rib [19].](image1)

![Figure 14. Multi-V-rib roughness [28].](image2)
The experimental parameter ranges were $Re = 4000–12,000$; $\alpha = 40^\circ–80^\circ$, and $p/e = 4–14$. The parameters $w/e = 4.5$ and $g/e = 1$ were fixed. The maximum increments in THPP and $Nu$ were 2.45 and 3.34 times, respectively, over the smooth duct. The best value of THPP was achieved near a $Re$ of 12,000. Patil et al. [27] analyzed the effect of V-shaped broken ribs combined with a staggered rib (Figure 17) on the performance of the SAH. The studies encompassed parameter ranges of $Re = 3000–17,000$; $p'/p = 0.2–0.8$; and $r/e = 1–2.5$ for a fixed value of $e/D_h = 0.043$, $g/e = 1$, $\alpha = 60^\circ$, and $p/e = 10$. The highest augmentation in $Nu$ was found up to 3.18 times over the smooth duct. Jain and Lanjewar [70] analyzed the thermohydraulic performance of the SAH by using a V-shaped rib with symmetrical gaps combined with staggered ribs. The parameters $p/e$ and $Re$ varied from 10 to 16 and 3000 to 14,000, respectively, for a fixed value of $p'/p = 0.65$, $\alpha = 60^\circ$, and $r/e = 4$. The highest augmentations in the friction factor and $Nu$ were 3.13 and 2.30, respectively, for $p/e = 12$.

Kumar and Kim [71,72] studied the effect of various ribs in V-form on the performance of the SAH in the $Re$ range of 5000–20,000. The various V-form ribs include V-rib. They used parameter values of $\alpha = 60^\circ$ and $e/D_h = 0.040$. They reported that a V-shaped rib combined with grooves shows the highest value of THPP as that of other investigated V-ribs of different arrangements. Nidhul et al. [73] used CFD and exergy analysis to study the effect of a secondary flow in the duct generated due to a V-shaped rib on the thermohydraulic performance of an SAH duct. $Re$ ranged from 5000 to 20,000. The value of $e/D_h = 0.05$,
and $p/e = 10$. The reported value of the highest augmentation in $Nu$ was 2.41 times over the smooth surface at $Re = 7500$ and $\alpha = 45^\circ$, and the maximum value of $f$ was 2.53 times over the smooth surface at $Re = 17,500$ and $\alpha = 60^\circ$. Mishra et al. [74] used CFD analysis for a V-shaped down rib with multigap and turbulence promoters (Figure 18) to study the performance of a triangular-duct SAH in the $Re$ range of 4000–20,000. The investigation covered an $\alpha$ range of 45° to 60° and a $p/e$ range of 8 to 14. The maximum thermal performance was achieved at $p/e = 10$ and $\alpha = 45^\circ$. The THPP increased as $Re$ increased from 4000 to 10,000, then thereafter decreased in the upper range of $Re$. Patel and Lanjewar [75] experimentally and numerically studied the effect of novel V-shaped ribs on the performance of the SAH. The study parameter varied as $p/e = 6–14$ whereas other parameters viz. $p'/p = 4, r/e = 4, g/e = 4, \alpha = 60^\circ, e/D_h = 0.043$ and $Ng = 3$ with Reynolds number in the range of 4000 to 14,500. The highest augmentation took place in $Nu = 1.55$ to 2.26 and the friction factor = 2.63 to 3.40 at $p/e$ equalling 10 and 8, respectively, in comparison with a smooth surface. The highest value of THPP = 1.59 was achieved at $p/e = 10$ and $Re = 12,364$. Further, Patel and Lanjewar [76] analyzed the effect of a V-shaped roughness geometry with staggered elements using additional gaps in symmetrically arranged elements of roughness (Figure 19) on the performance of the SAH. The distinct experimental parameters varied as $e/D_h$ equaled 0.043, $g/e$ equaled 4, $p/e$ equaled 10, $p'/p$ equaled 0.4, $Ng$ equaled 4, $d/w$ equaled 0.25 to 0.85, and $Re$ equaled 4000–15,000. The highest value of the THPP parameter was 1.82 at $d/w$ equalling 0.65 and $Re = 12,524$. Alam et al. [77–80] experimentally analyzed the effect of V-shaped perforated blocks (Figure 20) on the performance of the SAH. The study encompassed parameter ranges of $e/H$ = 0.4 to 1.0, $p/e$ = 4 to 12, $\alpha = 60^\circ$, and $Re$ = 2000 to 20,000. The highest augmentations in $Nu$ and $f$ were 6.76 and 28.84 over the smooth duct at $e/H = 0.8$ and $p/e = 8$. Further, Alam et al. [81] experimentally studied the effects of different types of perforation shapes on the performance of the SAH. They used square, rectangular, and circular types of perforation shapes in a 1–0.6 range of circularity. The value of $\alpha$ varied from 30° to 75°. The highest values of $Nu$ and $f$ were achieved at $\alpha = 60^\circ$. The noncircular shapes of perforation showed a higher thermal performance than that of circular shapes.

![Figure 17. V-shaped broken rib combined with staggered ribs [82].](image-url)
5.4. Multi-V-Shaped Ribs

Singh et al. [83] analyzed the effect of a multi-V-rib with multi uniform gaps on the performance of the SAH. The friction factor and $Nu$ were augmented 5.67 and 6.46 times in comparison with a smooth duct at $e/w = 0.866$, $x/w = 0.25$, $W/w = 6$, and $e/D_h = 0.0454$. The highest value of THPP equaling 4.24 was achieved. Kumar et al. [29] investigated the effect of a multi-V-shaped rib with gaps on the performance of a rectangular duct in a SAH, as shown in Figure 21. The ranges of various parameters were $Re$ varying from 2000 to 20,000 and $g/e = 0.5–1.5$. The fixed value of $\alpha = 60^\circ$, $e/D_h = 0.043$, and $p/e = 10$. 

Figure 18. V-shaped rib with multiple gaps and turbulators [74].

Figure 19. V-shaped roughness geometry with staggered elements [76].

Figure 20. V-shaped perforated blocks [80].
The friction factor and $Nu$ were augmented 6.13 and 6.32 times, respectively, in comparison with a smooth duct. The best value of THPP was achieved at $g/e = 1$ and $d/x = 0.69$. Further, Kumar et al. [84,85] studied the performance of this artificial roughness with the parameter’s $W/w = 6$, $W/e = 12$, $e/D_h = 0.0433$, and $g/e = 1.0$. The value of $\alpha$ ranged from $30^\circ$ to $75^\circ$. They reported that $f$ and $Nu$ are strong functions of $\alpha$, and also, they have a maximum value at $\alpha = 60^\circ$. Jin et al. [86–88] numerically analyzed the effect of an inline and staggered multi-V-shaped rib on the performance of the SAH. The staggered arrangement had highest enhancement of 26% and 18% in $Nu$ and THPP, respectively, over the inline arrangement of ribs. The maximum value of THPP was 2.43. Promvonge and Skullon [89] studied the effect of V-shaped flap-baffle and chamfered-grove vortex generators (VG) on the performance of a roughened duct, as shown in Figure 22. Both the flap baffle and VG were at $\alpha$ equal to $45^\circ$, and the experiment was performed in both the apex-up and apex-down pattern of a V-shaped flap baffle in the range of $Re = 5290–22,600$. The apex-up pattern had better performance in comparison with the apex-down pattern of V-shaped flap baffles. $Nu$ and the friction factor were enhanced remarkably by using this type of roughness. They reported that the maximum value of TEF was 2.68 at $Re = 5290$.

Figure 21. Multi-V-shaped rib with gap [29].

Figure 22. V-shaped flap-baffle and chamfered-grove vortex generators [89].
5.5. Arc-Shaped Ribs

Various researchers have numerically and experimentally investigated the effect of arc-shaped ribs on performance with respect to the flowing fluid and pattern of ribs on the duct surface. Yadav et al. [32] studied the effect of a circular protrusion that is in an angular arc pattern (Figure 23) for various parameters varying as \( p/e \) equal to 12–24 and \( \alpha' \) equal to 45°–75° and \( \text{Re} \) varying from 3600 to 18,100. The highest increments in friction factor \( f \) and Nusselt number \( \text{Nu} \) were reported to be 2.93 and 2.89 times, respectively, for \( p/e = 12 \) and \( e/D_h = 0.03 \).

Sahu and Prasad et al. [90] investigated the effect of an arc-shaped wire type of roughness on the performance of the SAH by using exergy efficiency analysis, as shown in Figure 24. The maximum augmentation in the exergetic efficiency corresponding to \( e/D_h \) equaled 0.0422, which was 56% as that of the smooth-plate SAH. The exergetic efficiency strongly depends on the various roughness parameters and \( \text{Re} \). Gill et al. [91,92] investigated the effect of a broken-arc rib combined with staggered rib pieces on the performance of the SAH. The experimental parameters encompassed \( r/g = 1 \) to 6, \( \alpha/90 = 0.333 \), \( p'/p = 0.4 \), \( W_1/w = 0.65 \), \( e/D_h = 0.043 \), and \( \text{Re} = 2000 \) to 16,000. The friction factor \( f \) and Nusselt number \( \text{Nu} \) were augmented 2.50 and 3.06 times as that of the smooth duct and 2.77 and 2.60 times over the broken-arc-type-rib roughened duct. The highest value of THPP was achieved at \( r/g = 4 \). On the same type of roughness, Hans et al. [33] further studied the effect of broken-arc-shaped artificial roughness (Figure 25) on the thermohydraulic performance of the SAH. The study encompassed parameters of \( p/e \) equal to 4–12, \( g/e \) equal to 0.5–2.5, \( e/D_h \) equal to 0.022–0.043, \( d/x \) equal to 0.2–0.8, \( \alpha' \) equal to 15°–75°, and \( \text{Re} \) varying from 2000 to 16,000.

![Figure 23. Arc-shaped protrusions as artificial roughness [32].](image)

![Figure 24. Arc-shaped artificial roughness [90].](image)

![Figure 25. Brocken-arc-shaped roughness [33].](image)
The augmentations in $f$ and $Nu$ were reported to be 2.44 and 2.63 times as that of the smooth duct. The corresponding values over the continuous arc-shaped rib were 1.19 and 1.14 times, respectively. Ghritlahre et al. [93] studied the performance of an arc-shaped artificially roughened duct with an apex-down and apex-up flow of air. They took a values of $p/e$ equal to 10, arc angle $= 60^\circ$, and $e/Dh = 0.0395$. The highest efficiency of the apex-up pattern was achieved at 73.2%, and for the apex-down pattern, it was 69.2%. The apex-up pattern performed 33.2% better in comparison with the apex-down arrangement. The thermal performance of the apex-up pattern was better as compared with the apex-down pattern of an arc-shaped artificially roughened duct. Yadav and Prasad [94] theoretically studied the effect of arc-shaped wire roughness on the performance of a parallel-flow SAH. The thermal efficiency of a roughened parallel-flow SAH was 8% to 10% higher in comparison with a smooth SAH. Ambade and Lanjewar [95] experimentally studied the effect of a symmetrical gap with arc-shaped roughness and a staggered element on the performance of the SAH at Re equal to 3000–15,000 and $p/e$ equal to 6–14. The fixed parameters were $p'/p = 3$, $g/e = 4$, $r/e$ equal to 4, $Ng$ equal to 3, and $\alpha'$ equal to 30°. They compared this geometry with the smooth duct and the duct having broken-arc-shaped rib roughness with staggered elements. The arc-shaped roughness with a new symmetrical gap augmented the friction factor and $Nu$ up to 4.15 and 2.04 times, respectively, over the broken-arc-shaped roughness with a staggered element, while augmentation in Nusselt number and friction factor were 2.18 and 3.88 times, respectively with corresponding smooth duct. Azad et al. [96] investigated the effect of a discrete-symmetrical arc type of rib roughness on the performance of the SAH. The values of the experimental parameters covered in the study were $e/Dh = 0.045$, $g/e = 2–5$, $Ng = 3$, $p/e = 10$, $\alpha' = 30^\circ$, and $Re = 3000$ to 14,000. The value of $g/e$ had a remarkable effect on the performance. The highest enhancement reported in $Nu$ was equal to 3.88 over the smooth duct at $g/e = 4$. The value of THPP ranged from 1.4 to 1.68 at $g/e = 4$, and the best value of THPP was 1.68 at Re equal to 14,000. Gill et al. [97] analyzed the effect of staggered broken-arc hybrid-rib roughness on the thermohydraulic performance of the SAH. The parameters of the study ranged as $e/Dh = 0.022–0.043$, $\alpha' = 15–75^\circ$, $p/e = 4–12$, and $Re = 2000–16,000$. The $f$ and $Nu$ were augmented 2.57 and 3.16 times over the broken-arc roughened duct. The highest value of THPP was reported to be 2.33. Sureandhar et al. [98] studied the effect of arc-rib fin-type roughness on the performance of the SAH. The experimental parameters of the study varied as $e/Dh = 0.04222–0.0541$, $\alpha/90 = 0.3333$, and $p/e = 10$. $Nu$ and THPP increased as the mass flow rate increased, while the friction factor decreased.

5.6. Multi-Arc-Shaped Ribs

Various researchers numerically and experimentally analyzed the effect of a multi-arc-shaped rib on thermohydraulic performance with respect to the flowing fluid and attachment arrangement of roughness on the duct surface. Kumar et al. [99] experimentally analyzed the effect of a discrete arc-shaped rib on the performance of the SAH. The ranges of the parameters in the study were $g/e = 0.5–1.5$, number of gaps = 1–3, and $d/x = 0.3–0.9$. The optimum value of THPP was equal to 3.85 achieved at $W/w = 1$, $d/x = 0.6$, and number of gaps = 3. Saravankumar et al. [100] investigated the effect of arc-shaped ribs with fins and baffles on the performance of the SAH. They reported that the exergy and effective efficiency were augmented by 28.3% and 27.1%, respectively, in comparison with the SAH duct with an arc-shaped rib. Further, Saravankumar et al. [101] studied the exergetic performance of the SAH duct with arc-shaped roughness with fins and baffles. They reported the exergy efficiency to be equal to 5.2% in the optimum conditions. Agrawal and Bhagoria [102] experimentally investigated the effect of a discrete type of roughness without a gap in a double-reverse arc pattern on the thermohydraulic performance of the SAH. They considered experimental parameters of, first, $p/e = 6.67$ to 11.67 and $\alpha' = 60^\circ$, and after that, $p/e = 8.33$ and $\alpha' = 30^\circ$ to 75°. They reported the highest augmentation value of $Nu = 134.63$ at $\alpha' = 60^\circ$, $e/Dh = 0.027$, and $Re = 3010$. The friction factor at $\alpha' = 60^\circ$, $e/Dh = 0.027$, and $Re = 3010$ was 0.0342. Hassan et al. [103] studied the effect of
a multiarc dimple-shaped roughness (Figure 26) on the performance of the SAH. They covered experimental parameters of $p/e$ equal to 4–16, $W/w$ equal to 1–5, $e/D_h$ equal to 0.018–0.036, $\alpha'$ equal to 30°–75°, and Re equal to 2000–18,000. They reported that the highest value of $Nu$ was 3.19 to 5.56 times that of the smooth duct at $p/e$ equal to 12. The value of $Nu$ increased up to $e/D_h$ equal to 0.036; after that, it decreased. The enhancement in the friction factor equaled 1.36 to 2.27 times in comparison with the smooth duct at $e/D_h$ equal to 0.045. Agrawal et al. [104] experimentally investigated the effect of a double-arc reverse rib with even gaps on the performance of a solar collector. The values of the fixed parameters were $e/D_h = 0.027$, $W/H = 8$, and $I = 1000$ W/m². The value of the variable parameter varied as $p/e$ equal to 10, $\alpha$ equal to 30°–75°, and Re equal to 3000–14,000. The maximum augmentations in $f$ and $Nu$ were found to be 2.42 and 2.85 times over the smooth surface. The highest value of THPP equal to 2.41 was noticed at $p/e = 10$ and $e/D_h = 0.0270$.

Figure 26. Multiarc dimple-shaped roughness [103].

5.7. W-Shaped Ribs

Various researchers numerically and experimentally analyzed the effect of W-shaped ribs on performance with respect to the flow of air and the attachment pattern of a rib on the surface an SAH duct. Lanjewar et al. [36] studied the performance of a SAH duct with a W-shaped rib type of roughness in both a W-down and W-up pattern of the artificial roughness. The values of various parameters taken were $e/D_h$ equal to 0.03375, Re range of 2300–14,000, and $p/e$ equal to 10. The ranges of THPP were 1.21 to 1.73 and 1.46 to 1.95, respectively, for top-up and top-down patterns. The W-down pattern of artificial roughness had better performance in comparison with the W-up pattern. Kumar et al. [38] studied the effects of a discrete-W-shaped rib (Figure 27) on the performance of the SAH in the Re range of 3000 to 15,000. The value of the parameter $p/e$ was fixed at 10, $e/D_h$ varied from 0.0168 to 0.0338, and $\alpha$ varied from 30° to 75° during the experiment. The highest augmentations in the friction factor and $Nu$ were found to be 2.75 and 2.16 at $e/D_h = 0.0338$ and $\alpha = 60°$. Kumar et al. [105] investigated the effect of W-shaped ribs with a booster mirror on the performance of the SAH. The combination of W-shaped roughness with a booster mirror enhanced $Nu$, St, and the friction factor by 29–38%, 31–39%, and 23–29% in comparison with that without a booster mirror.

Figure 27. W-shaped artificial roughness [106].

5.8. L-Shaped Ribs

Gawande et al. [39] studied the effect of reverse L-shaped repeated rib artificial roughness on the convective performance of the SAH through experimentation and CFD analysis,
as shown in Figure 28. The effect of L-shaped roughness was studied in the ranges of parameters of $p/e = 7.14–17.86$ and Re = $3800–18,000$; however, the value of $e/D_h$ was fixed at 0.042. The highest enhancement in $Nu$ was found up to 2.827 times as that of the smooth duct at $p/e = 7.14$ and Re = 15,000. The highest augmentation in the friction factor was found up to 3.424 times over the smooth duct at $e/D_h = 0.042$, Re = 3800, and $p/e = 7.14$. THPP was found to be in the range of 1.92 to 1.90 by using this repeated roughness.

Figure 28. L-shaped artificial roughness [39].

5.9. S-Shaped Ribs

Kumar et al. [40] studied the effect of an arc-shaped wire rib arranged in an ‘S’ type of pattern (Figure 29) on the performance of the SAH. The study considered various parameter ranges of $e/D_h = 0.022–0.054$, $p/e = 4–16$, $W/w = 1–4$, $\alpha = 30^\circ–75^\circ$, and Re = $2400–20,000$. The utilization of arc-shaped roughness in an ‘S’ type of pattern augmented the friction factor and $Nu$ 2.71 and 4.64 times, respectively, in comparison with a smooth duct at the parameter’s $p/e$, $W/w$, and $\alpha$ at 8, 3, and $60^\circ$ respectively. Wang et al. [107] analyzed the effect of an S-shaped rib with gaps (Figure 30) on the performance of the SAH. The various parameters varied as Re = $2000$ to $20,000$, $p/e = 20$ to $30$, $e/D_h = 0.023$ to $0.036$, $W/w = 3$ to 5, and $g/e = 1$ to 2. The highest increase in $Nu$ was found 5.42 times as that of the smooth duct at the parameters $p/e = 20$, $W/w = 4$, and Re = 19,258. The highest increase in $f$ was 5.87 times over the smooth duct.

Figure 29. Arc-shaped wire ribs arranged in an ‘S’ type of pattern [40].

Figure 30. S-shaped ribs with gaps [107].
5.10. Delta Winglet-Shaped Ribs

Baisi et al. [108] studied the effect of a longitudinally curved delta-shaped vortex generator with perforation and without perforation type of roughness on the performance of the SAH. The experimental parameters covered a range of parameters as Re = 2500–12,000, e/Dh = 0.8, and α = 45°. The friction factor and Nu were augmented 45.83 and 6.94 times in comparison with a smooth duct. The best value of TEF was equal to 2.26 at Re = 11,382. Kumar and Layek [109,110] analyzed the performance of a SAH duct with the help of winglet types of vortex generators (Figure 31). The experimental parameters covered the ranges of parameters as p/e = 5–12, α = 30°–75°, W/w = 3–7, and Re = 3000–22,000. The optimum value of Nu was achieved at α = 60° and p/e = 8. Kumar et al. [111] analyzed the performance of the SAH by using delta-shaped winglets with perforation. The thermohydraulic performance had a maximum value of 3.14 at Re = 12,000 and with a zero spacer length. The f and Nu were augmented 4.52 and 5.17 times, respectively, as that of the smooth duct. Promvonge et al. [112] analyzed the effect of a punched delta-shaped winglet type of roughness in the duct of the SAH. The experimental parameters covered the ranges of parameters as P/R varying from 1 to 2, d/R varying from 0 to 0.583, Re varying from 4000 to 24,000, and angle of attack equal to 30°. Nu was enhanced in the range of 17.1 to 78.21, and the friction factor was augmented in the range of 3.92 to 5.9 in comparison with a smooth duct.

Figure 31. Winglet types of vortex generator [109].

5.11. Quarter Circular-Shaped Ribs

Mahanand and Senapati [113] numerically studied the performance of the SAH by using quarter circular-shaped ribs. The p/e varied from 7.14–17.86, Re varied from 3800 to 38,000 and e/Dh = 0.042. Nu and f were augmented 2.7816 and 3.4355 times at Re equal to 15,000 and 3800 and p/e equal to 7.14, respectively. The thermal augmentation ratio had a maximum value of 1.88 at e/Dh equal to 0.042, Re equal to 15,000, and p/e equal to 7.14.

5.12. Dimple/Protrusion-Shaped Roughness

Bhushan and Singh [41] studied the effect of a protrusion type of roughness (Figure 32) on the performance of the SAH. The study parameters encompassed S/e = 18.75 to 37.50, L/e = 25.00 to 37.50, e/Dh = 0.03, W/H = 10, d’/D = 0.147–0.367, and Re = 4000 to 20,000. The protruded duct surface had a higher value of convection coefficient in comparison with a smooth duct. The highest values of f and Nu were 2.2 and 3.8 times as that of the smooth duct. The highest augmentation in convection coefficient occurred at L/e = 31.25 and d/D = 0.294. Gilani et al. [114] experimentally investigated the effect of pin-type protrusions of conical shape on the performance of the SAH. The staggered arrangement pattern of protrusion was much more effective compared with the inline pattern arrangement by up to 15% at Ra = 50,000 to 75,000. They tested three types of conical pin protrusions of 2, 3, and 4-mm height. The experiment was performed at pith values of 16, 32, and 48 mm. The highest value of Nu was achieved at p = 16 mm, and the efficiency was enhanced by 26.5% at this pith value. Perwez and Kumar [115] analyzed the thermal performance
of the SAH with spherical dimple-shaped roughness at the absorber plate at Re varying from 1900 to 6000. The maximum value of convection coefficient was 20.23 W/m²K, and the instantaneous thermal efficiency was 23.45–35.50% higher in comparison with a smooth duct.

5.13. Pentagonal Shape Ribs

Debnath et al. [116] analyzed the thermal performance of pentagonal rib roughness on the performance of a SAH duct with the help of a CFD code. The values of various investigation parameters were taken as Re = 12,633–62,842, $e/D_h = 0.045–0.084$, and $p/e = 6.43–8$. The optimum configurations of various parameters were found as $e/D_h$ equal to 0.045 and Re equal to 38,414. The augmentations in the friction factor and $Nu$ at optimum configuration were 67.2% and 70%, respectively, over the smooth duct.

5.14. Stepped Cylinder Ribs

Antony et al. [117] numerically analyzed the effect of stepped-cylinder-rib-type roughness on the performance of the SAH in the Re range of 3000 to 24,000. The core diameter of the artificial roughness varied from 3 mm to 7 mm with a step of 1 mm. The experimental parameters encompassed the range of parameters as $p/e = 11.11–27.78$ and number of steps in the roughness varying from 1 to 3. The maximum augmentation in $Nu$ number was found to be 76.41 at Re = 24,000. A TEP and THPP of 1.14 and 1.49 were achieved at Re of 15,000 and 18,000, respectively.

Figure 32. Protrusion-type roughness [41].

5.15. NACA Profile Ribs

Patel et al. [118] analyzed the effect of reverse NACA 0040 type of profile rib on the performance of the SAH in the Re range of 6000 to 18,000. A THPP of 2.53 was achieved at Re = 6000. A maximum value of $Nu$ of 104.45 was achieved at Re = 18,000.

5.16. C-Type Rib Roughness

Gabhane and Kanase-Patil [119] analyzed the effect of multi-C-type rib roughness (Figure 33) on the performance of the SAH. The experimental parameters covered the ranges of parameters as $p/e = 8$ to 40, Re = 3000 to 15,000, and $\alpha = 30°$ to $60°$. The values of rib height, duct aspect ratio, and $e/D_h$ were 2 mm, 10, and 0.02, respectively. The highest value of $Nu$ was found to be 415 at Re = 15,000 and $p/e = 24$. The value of THPP was equal to 3.48. Saravanan et al. [120] studied the effect of the staggered multi-C-shape finned surface of the absorber on the performance of the SAH. They investigated both
perforated and nonperforated surfaces of the absorber. The experimental parameters varied as \( p/g = 3.4–3.8 \) and \( Re = 3000–27,000 \). The secondary flow generated along the surface of the fin and the mixing of the secondary flow developed in the duct with the mainstream of flow enhanced the level of turbulence remarkably. In the case of perforated surface, the friction factor \( Nu \) was augmented 5.34 and 2.67 times as that of the smooth duct at \( p/g = 3.8 \). In the case of a nonperforated surface, the friction factor and \( Nu \) were augmented 5.93 and 2.61 times over the smooth duct.

![Figure 33. Multi-C-type rib roughness [119].](image)

5.17. Twisted Tapes

Kumar and Layek [121,122] analyzed the effects of twisted ribs on the performance of the SAH for \( Re \) of 3500 to 21,000. The experimental parameter varied as \( \alpha = 30–90^\circ \), \( p/e = 6–10 \), and \( y/e = 3 \) to 7. The highest augmentations in \( f \) and \( Nu \) were 1.78 and 2.58 times over the smooth duct. Further, Kumar and Layek [123] also performed numerical analysis for optimizing the exergetic efficiency and energetic efficiency by using the same type of rib roughness. The highest augmentation ineffective efficiency, thermal efficiency, and exergetic efficiency were equal to 1.79, 1.81, and 1.81 times over the smooth duct at a twist ratio equal to 3 and \( p/e = 8 \).

5.18. Hyperbolic-Shaped Ribs

Thakur et al. [124] analyzed the performance of the SAH by using hyperbolic-shaped (Figure 34) artificial roughness with the help of a CFD code. They analyzed the performance in the parameter range of \( p \) equal to 10 to 20 mm and \( e \) equal to 0.5 to 2 mm. The best performance of the SAH was achieved at \( e = 1 \) mm, \( p = 10 \) mm, and \( Re = 6000 \).

![Figure 34. Hyperbolic-shaped ribs [124].](image)

5.19. Wedge-Shaped Rib

Bhagoria et al. [46] investigated the effect of wedge-shaped ribs (Figure 35) in transverse arrangement on the performance of the SAH. The experimental parameter ranged as \( e/D_h = 0.015–0.033 \), \( Re = 3000–18,000 \), \( p/e = 60.17\phi^{−1.0264} < p/e < 12.12 \), and \( \alpha = 8^\circ–15^\circ \). The friction factor and \( Nu \) were augmented 5.3 and 2.4 times, respectively. The highest heat transfer performance was achieved at \( \phi \) about 10\(^\circ\) and \( p/e = 7.57 \). \( Nu \) decreased on both sides of this wedge angle.
5.2. Spherical-Ball-Type Roughness

Manjunath et al. [15] numerically investigated the effect of spherical turbulators (Figure 36) on the performance of the SAH. The study parameter encompassed a turbulator diameter varying from 5 to 25 mm, Re ranging from 4000 to 25,000, and $p/e$ varying from 3 to 12. The thermal efficiency increased as the value of $p/e$ decreased and also as the diameter of the sphere increased. The maximum value of $Nu$ was equal to 2.5 times as compared with the smooth duct at $p/e = 3$ and Re = 23,560. The thermal efficiency increased up to 23.4% over the smooth surface. Kumar and Murmu [125,126] experimentally studied the effect of a spherical ball type of roughness in an inclined pattern (Figure 37) on the performance of a roughened duct. The experimental parameter varied as $p/e = 9$ to 18, $\alpha = 35$ to 75°, $e/d_b = 0.5$ to 2, and Re = 2500 to 18,500. They reported that the highest thermal efficiency achieved was 81.30% at $\alpha = 55^\circ$, $e/d_b = 1$, and $p/e = 15$. The lowest thermal efficiency was achieved at $p/e = 9$.

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**Figure 35.** Wedge-shaped roughness [46].

**Figure 36.** Spherical turbulators [125].

**Figure 37.** Spherical ball type of roughness in an inclined pattern [126].
5.21. Combination of Different Types of Ribs

Promvonge et al. [127] investigated the effect of a V-shaped rib and delta groove on the performance of the SAH. Re ranged from 7000 to 30,000, and $\alpha$ was equal to 60°. The highest value of thermal performance was achieved at $e/H = 0.108$ and $p/H = 1.0$. Sharma and Kalamkar [128] experimentally and numerically studied the effects of distinct arrangements of ribs on the performance of the SAH. For one pitch length, two truncated and two thin-transverse-continuous ribs were used. The study parameters encompassed $e/H = 0.1$, $e/D_h = 0.055$, $\alpha = 90^\circ$, Re = 4000–16,000, and $p/e = 10$. Rib arrangement in a roughened duct had a remarkable effect on the performance of the SAH. Case 1 of rib arrangement showed the highest augmentation in average $Nu$ equal to 49.28. Case 4 showed the highest augmentation in friction factor equal to 2.88 to 7.18 over the smooth duct.

Prakash and Saini [129] studied the effect of a special type of roughness containing spherical protrusion along with inclined-rib protrusions on the performance of the SAH. The inclined-rib protrusions lay in between the spherical protrusions. The experimental parameter varied as $p/e = 15–30$, Re = 2000–20,000, $g/e = 14$, $e/D_h = 0.04$, and $\alpha = 60^\circ$. The augmentations in $f$ and $Nu$ were reported as 1.58 and 2.88 times as that of the smooth duct. The highest value of THPP was equal to 3.66 at $p/e = 25$. Luo et al. [130] numerically studied the effect of a delta winglet vortex generator combined with a dimple type of roughness on the performance of the SAH. Re ranged from 4000 to 40,000. The $f$ and heat transfer were enhanced by 36.29% and 36.23%, respectively. Skullong et al. [131] experimentally studied the effect of wavy-rib-grove turbulators (Figure 38) on the heat transfer performance of the SAH. The experimental parameter varied as $e/H = 0.25$, $p/H = 0.5$ to 2, and Re = 4000 to 21,000. The wavy rib was at $\alpha = 45^\circ$ with respect to the flow stream. The rib-grove pattern on the upper and lower walls of the duct showed the highest performance at $p/H = 0.5$. Kumar et al. [132] numerically studied the effect of polygon- and trapezoid-shaped ribs on the performance of the SAH. The value of the parameter $e/D_h$ ranged from 3.33 to 20, $p/e$ from 0.03 to 0.09, and Re from 3800 to 18,000. The highest augmentation in $Nu$ equal to 2.483 was achieved in comparison with a smooth surface. The highest value of THPP equal to 1.89 was achieved at $e/D_h = 0.06$ and $p/e = 10$. Tanda and Satta et al. [133] analyzed the effect of 45° angled and intersecting rib roughness on the performance of a rectangular duct as shown in Figure 39. The intersecting ribs were parallel to the stream of flow. The intersecting ribs enhanced the turbulence level in the duct due to which the thermohydraulic performance improved. The augmentation in $Nu$ was slightly larger when two intersecting ribs were used instead of one intersecting rib. Farhan et al. [134] numerically studied the effect of a V-shape rib corrugated surface integrated with a twisted tape type of roughness (Figure 40) on the exergetic and energetic efficiency of the SAH. The thermal performance with twisted tape inserts in the channels had a remarkable increase in comparison with that without a twisted tape insert. It was 74.42% at Re = 12,000 and 68% in the case of that without a twisted tape insert.

Figure 38. Wavy-rib-grove turbulators [135].
5.22. Other Roughnesses

Singh and Singh [42] studied the effect of transverse ribs with a square wave type of profile (Figure 41) on the thermohydraulic performance of the SAH by using a CFD code. The value of Re varied from 3000 to 15,000, and $p/e$ varied from 4 to 30. The value of $e/D_h = 0.043$ was fixed. The highest augmentations in friction factor and $Nu$ were found to be 3.55 and 2.14 times that of the smooth duct at Re = 15,000. They reported the highest value of THPP as 1.43 at Re = 12,000 and $p/e = 10$. Ansari and Bazargan [136] investigated the effect of $L/H$, $e/D_h$, $p/e$, and $W/H$ on the heat transfer performance of the SAH. They reported that the optimum value of $e/D_h$ incremented as the value of the rate of flow decreased. The overall efficiency of the SAH was enhanced by more than 9% with the help of a ribbed surface. Alfarawi et al. [137] analyzed the effect of hybrid-rib roughness of rectangular and semicircular cross sections on the performance of the SAH. The study parameters encompassed $p/e = 6.6$ to 53.3 and Re = 12,500 to 86,500. The enhancements in the friction factor and $Nu$ were 1.8 to 4.2 and 1.3 to 2.14, respectively. The highest increase in heat transfer was achieved at $p/e = 6.6$ in the case of hybrid ribs. Alam and Kim [138] numerically investigated the effect of a semi-elliptical-shaped obstacle type of roughness in a V-down pattern on the performance of the SAH. The parameter varied as $\alpha = 30^\circ$–90° and Re = 6000–18,000. The pattern of obstacles on the duct surface and $\alpha$ had a remarkable impact on thermal performance due to a high level of turbulence. The highest
augmentations in $f$ and $Nu$ were 6.93 and 2.05, respectively, at $\alpha = 75^\circ$ for a staggered pattern. Xiao et al. [139] numerically investigated the effect of inclined trapezoid-shape turbulators on the thermohydraulic performance of the SAH. $Nu$ increased significantly, and energy efficiency was augmented by 24% and exergy efficiency was augmented by 31% over the smooth duct.

Table 3. Values of $\alpha$ at which the highest heat transfer rate for distinct geometries of roughness is investigated in the SAH duct.

| S. No. | Investigators | Type of Roughness | Value of $\alpha$ |
|--------|---------------|-------------------|-------------------|
| 1      | Aharwal et al. [17] | Inclined rib with gaps | 60 |
| 2      | Gupta et al. [23] | Continuous inclined rib | 60 |
| 3      | Momin et al. [24] | V-shaped continuous rib | 60 |
| 4      | Maithani and Saini [25] | V-shaped rib with symmetrical gaps | 60 |
| 5      | Deo et al. [26] | Multi-V-shaped rib with gaps combined with staggered rib | 60 |
| 6      | Patil et al. [27] | V-shaped rib with gaps combined with staggered rib | 60 |
| 7      | Hans et al. [28] | Continuous multi-V-rib | 60 |
| 8      | Kumar et al. [29] | Multi-V-shaped rib with gap | 60 |
| 9      | Sethi et al. [31] | Dimple rib in arc pattern | 60 |
| 10     | Yadav et al. [32] | Dimple rib in arc pattern | 60 |
| 11     | Pandey et al. [34] | Multiarc rib with gap | 60 |
| 12     | Singh et al. [35] | Multiarc rib | 60 |
| 13     | Lanjewar et al. [36,37] | Continuous W-rib | 60 |
| 14     | Kumar et al. [38] | Discrete W-rib | 60 |
| 15     | Kumar et al. [40] | S-shaped rib | 60 |
| 16     | Saini and Saini [43] | Expanded metal mesh | 61.9 |

Figure 41. Transverse rib with square wave type of profile [42].

Manjunath et al. [140] numerically investigated the effect of a sinusoidal profile type of a duct surface on the performance of the SAH. Re varied from 4000 to 24,000. The sinusoidal type of the surface enhanced the level of turbulence significantly, which led to a remarkable increment in convection coefficient. The thermal efficiency increased up to 12.5% over the smooth surface at the aspect ratio of the duct equaling 1.5. Bezbarah et al. [141] studied the effect of a conical vortex generator type of artificial roughness on the performance of the SAH. They used experimental parameters as $e/D_h = 0.17-0.34$, Re = 3000–16,000, and $p/e = 8-15$. The highest value of $Nu = 142.4$ was achieved at $e/D_h = 0.34$, $p/e = 8$, and Re = 16,000 as that of a smooth duct. The highest value of $f$ equaled 0.167 reported at $p/e = 8$, $e/D_h = 0.34$, and Re = 3500. The heat transfer performance was augmented by 192.2%. Dong et al. [142] numerically investigated the effect of an incline-grove ripple type of roughness on the performance of the SAH at Re in the range of 12,000–24,000. The incline-grove on the ripple surface enhanced the level of turbulence remarkably. The optimum value of $\alpha$ was near 45° to 60°.
Nu was augmented 1.04 to 1.946 times over the smooth surface. Alam et al. [143,144] numerically investigated the effects of conical protrusions on the thermohydraulic performance of the SAH. The study parameter varied as \( e/D_h = 0.02 \) to 0.044 and \( p/e = 6 \) to 12. The conical protrusion type of artificial rib roughness had a remarkable effect on the effective efficiency of the SAH. They reported the maximum value of effective efficiency as 70.92\% at \( e/D_h = 0.0289 \) and \( p/e = 10 \). Kumar and Goel [145,146] analyzed the effects of a distinct type of rib roughness on the thermohydraulic performance of the SAH by using a triangular cross-section channel. The performance of the SAH strongly depended on the cross section of artificial roughness and also the cross section of a flow passage. A rectangular cross-section rib with forwarding chamfering showed the highest THPP at 2.75. Further, Goel et al. [147] analyzed the effect of the hemispherical dimple cavity type of roughness on the performance of the SAH by using a triangular cross-section channel. The leading edge of the dimple-cavity-type roughness showed lower heat transfer than that of a trailing edge. The highest augmentation value of \( \text{Nu} \) equal to 5.33 was achieved at \( Re = 2160 \). The value of THPP was equal to 3.48. Xi et al. [148] numerically studied a ribbed channel for \( Re \) ranging from 10,000 to 90,000. The study parameter ranged as \( e/D \) varying from 0.05 to 0.15 and rib angle varying from 30° to 90°.

### 6. Performance Evaluation Parameters

A large number of rib roughness geometries have been investigated by researchers, which are employed in the SAH [149–151]. The maximum augmentation in Nusselt number and friction factor is listed in Table 4 for ready reference. A Nusselt number and friction factor correlation were developed in terms of Reynolds number and roughness parameters for various rib configurations; the details are given in Table 5. The performance of a roughened duct depends on many parameters, such as \( e/D_h \), \( \alpha \), \( p/e \), \( Re \), \( e/H \), \( d/w \), and \( W/H \), and also on duct shape and size. These parameters are important for determining the \( Nu \), friction factor, and THPP characteristic of the flow process in the duct of the SAH.

| Investigators      | Type of Roughness             | Parameter Used          | Augmentation |
|--------------------|-------------------------------|-------------------------|--------------|
| Prasad and Saini [13] | Continuous transverse rib    | \( e/D = 0.02-0.033 \) | \( Nu/Nu_s = 2.35 \) |
| Singh et al. [16]   | Nonuniform saw-tooth-shaped rib | \( e/D_h = 0.043, p/e = 8 \) | \( Nu/Nu_s = 1.78 \) |
| Aharwal et al. [17] | Inclined rib with gaps       | \( \alpha = 30^\circ-90^\circ \) | \( Nu/Nu_s = 2.83 \) |
| Singh et al. [18,19] | V-shape with gap             | \( d/W = 0.16-0.67 \) | \( Nu/Nu_s = 3.04 \) |
| Sahu and Bhagoria [20] | Broken transvers ribs   | \( p = 10-30 \text{ mm} \) | \( h/h_s = 1.25-1.4 \) |
| Yadav and Bhagoria [21] | Triangular-shaped ribs       | \( Re = 800-18,000 \) | \( Nu/Nu_s = 3.07 \) |
| Yadav and Bhagoria [22] | Square shape ribs           | \( e/D_h = 0.021-0.042, Re = 000-18,000 \) | \( Nu/Nu_s = 2.86 \) |
| Gupta et al. [23]   | Continuous inclined ribs     | \( e/D = 0.023-0.050 \) | \( \eta/\eta_s = 1.16-1.25 \) |
| Momin et al. [24]   | V-shaped continuous rib      | \( e/D_h = 0.02-0.034 \) | \( Nu/Nu_s = 2.30 \) |
| Investigators          | Type of Roughness                                      | Parameter Used                               | Augmentation |
|------------------------|-------------------------------------------------------|----------------------------------------------|--------------|
| Maithani and Saini [25]| V-rib with symmetrical gaps                           | $\alpha = 30^\circ - 75^\circ$ $N_2 = 1 - 5$ $g/e = 1 - 5$ $p/e = 6 - 12$ $n = 2$ $e/D_b = 0.026 - 0.057$ $w/e = 4.5$ $p/e = 4 - 14$ $p/P = 4.5$ $g/e = 1$ $\alpha = 60^\circ$ $e/D = 0.0433$ $p'/p = 0.2 - 0.8$ $s'/s = 0.2 - 0.8$ $p/e = 10$ $\tau/e = 1 - 2.5$ $\alpha = 60^\circ$ | $Nu/Nu_i = 3.6$ $f/f_s = 3.67$ |
| Deo et al. [26]        | Multiple V-rib with gaps combined with staggered rib  | $W/w = 1 - 10$, $e/D = 0.019 - 0.043$ $\alpha = 30^\circ - 75^\circ$, $p/e = 6 - 12$ $g/e = 0.5 - 1.5$ $G_{th}/L = 0.24 - 0.80$ $e/D = 0.019 - 0.043$ $W/w = 1 - 10$, $p/e = 6 - 12$ $\alpha = 30^\circ - 75^\circ$ | $Nu/Nu_i = 4.7$ $f/f_s = 4.3$ |
| Patil et al. [27]      | V-rib with gap combined with staggered rib             | $W/w = 1 - 10$, $e/D = 0.019 - 0.043$ $\alpha = 30^\circ - 75^\circ$, $p/e = 6 - 12$ $g/e = 0.5 - 1.5$ $G_{th}/L = 0.24 - 0.80$ $e/D = 0.019 - 0.043$ | $Nu/Nu_i = 6.74$ $f/f_s = 6.37$ |
| Hans et al. [28]       | Continuous multiple V-rib                             | $\alpha = 30^\circ - 75^\circ$, $p/e = 6 - 12$ $\alpha = 30^\circ - 75^\circ$, $e/D = 0.019 - 0.043$ | $Nu/Nu_i = 6$ $f/f_s = 4.3$ |
| Singh et al. [35]      | Multiple-arc rib with gaps                            | $d/w = 0.25 - 0.85$ $g/e = 0.5 - 2$ $p/e = 4 - 16$ $\alpha = 30^\circ - 75^\circ$ | $Nu/Nu_i = 5.85$ $f/f_s = 4.96$ |
| Pandey et al. [34]     | Discrete W-rib                                        | $d/w = 0.25 - 0.85$ $g/e = 0.5 - 2$ $p/e = 4 - 16$ $\alpha = 30^\circ - 75^\circ$ | $Nu/Nu_i = 5.07$ $f/f_s = 3.71$ |
| Saxena and Verma [36]  | Continuous W-rib                                      | $\alpha = 30^\circ - 75^\circ$, $p/e = 10$ | $Nu/Nu_i = 2.36$ $f/f_s = 2.01$ |
| Kumar et al. [38]      | Discrete W-rib                                        | $\alpha = 30^\circ - 75^\circ$, $p/e = 10$ | $Nu/Nu_i = 2.16$ $f/f_s = 2.75$ |
| Gawande et al. [39]    | L-shaped rib                                          | $\alpha = 30^\circ - 75^\circ$, $p/e = 10$ | $Nu/Nu_i = 2.827$ $f/f_s = 2.434$ |
| Kumar et al. [40]      | S-shaped rib                                          | $W/w = 1 - 4$ $p/e = 4 - 16$ $\alpha = 30^\circ - 75^\circ$, $e/D = 0.018 - 0.045$ | $Nu/Nu_i = 4.64$ $f/f_s = 2.71$ |
| Bhushan and Singh [41] | Protrusion roughness                                  | $L/e = 25 - 37.5$ $S/e = 18.75 - 37.5$ $d/D_b = 0.0147 - 0.0367$ $\phi = 8^\circ - 15^\circ$, $p/e = 4.7 - 12.12$ | $Nu/Nu_i = 3.8$ $f/f_s = 2.2$ |
| Bhogoria et al. [47]   | Wedge-shaped ribs                                     | $\phi = 8^\circ - 15^\circ$, $p/e = 4.7 - 12.12$ | $Nu/Nu_i = 2.4$ $f/f_s = 5.3$ |
Table 4. Cont.

| Investigators            | Type of Roughness                                      | Parameter Used                                      | Augmentation |
|--------------------------|--------------------------------------------------------|-----------------------------------------------------|--------------|
| Singh I and Singh S [42] | Transverse rib with square wave profile                | $p/w = 4-30$, $c/D_h = 0.043$, $Re = 3000-15,000$   | $Nu/Nu_s = 2.14$ |
| Alam and Kim [137]       | Semiellipse-shaped obstacle                             | $p/w = 3.5$, $a = 30°-90°$, $Re = 6000-18,000$    | $Nu/Nu_s = 2.05$, $f/f_s = 5.3$ |
| Karmare and Tikekar [44] | Metal grit                                              | $e/D_h = 0.035-0.044$, $l/s = 1-1.72$, $p/w = 12.5-36$ | $Nu/Nu_s = 1.87$, $f/f_s = 6.93$ |
| Layek et al. [48]        | Chamfered rib combined with groove                      | $c/D_h = 0.022-0.04$, $\phi = 5°-30°$, $p/w = 4.5-10$ | $Nu/Nu_s = 3.24$, $f/f_s = 3.74$ |

Table 5. Correlations developed by researchers for different roughened surfaces.

| Investigators            | Roughness                                      | Correlations |
|--------------------------|------------------------------------------------|--------------|
| Aharwal et al. [17] (2009)| Inclined rib with gap                          | $Nu = 0.0102(e/D_h)^{0.51}Re^{1.148} \left\{1 - \left(0.25 - \frac{d}{w}\right)^2 \left\{0.01(1-g/e)^2\right\}\right\}$ |
| Verma and Prasad [60] (2000) | Wire roughness                                 | $Nu = 0.0731\times 10^{0.55}Re^{0.918}$             |
| Ebrahim-Momin et al. [24] (2002) | V-shaped continuous ribs                     | $f = 0.245(e/D_h)^{0.245}(p/e)^{-0.206}Re^{-1.25}$ |
| Istanto et al. [152] (2016) | V-shaped rib                                   | $Nu = 0.067Re^{0.884}(\alpha/60)^{-0.077}(e/D_h)^{0.424} \exp\left[-0.728\ln(\alpha/60)\right]^{2}$ |
| Singh et al. [19] (2011)       | V-shape with gap                               | $f = 6.266Re^{-0.425}(\alpha/60)^{-0.093}(e/D_h)^{0.565} \exp\left[-0.719\ln(\alpha/60)\right]^{2}$ |
| Maithani and Saini [25] (2016) | V-ribs with symmetrical gap                    | $Nu = 0.016Re^{0.893}(\alpha/90)^{-1.123} \exp\left[-1.107\ln(\alpha/90)\right]^{2}$ |
| Deo et al. [26] (2016)        | Multi-gap-V-down rib                          | $Nu = 2.36 \times 10^{-3}(p/e)^{3.58}Re^{0.90}(e/D_h)^{0.42}(d/w)^{-0.043}(\alpha/60)^{-0.023}$ |
| Saini and Verma [46] (2008)   | Dimple shape                                   | $f = 4.13 \times 10^{-2}Re^{-0.126}(e/D_h)^{0.75}(p/e)^{2.24}(d/w)^{-0.058}(\alpha/60)^{-0.034}$ |
| Hans et al. [28] (2010)       | Continuous multi-V-ribs                        | $Nu = 2.6 \times 10^{-6}Re^{0.93}(\alpha/60)^{0.111}\exp\left[-0.055\ln(\alpha/60)\right]^{2}$ |

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Table 5. Cont.

| Investigators          | Roughness                      | Correlations                                                                 |
|------------------------|--------------------------------|-------------------------------------------------------------------------------|
| Singh et al. [83] (2021)| Multi-V-ribs with uniform gap | \[
Nu = 0.0187Re^{1.176} \times (p/e)^{-0.6596} \times (e/D_h)^{0.4927} \\
\times (e/w)^{0.033} \times (W/w)^{0.0676} \times (g/e)^{0.1703} \times (x/w)^{0.1147} \\
\times \exp \left[ -0.0111\ln(W/w) \right]^2 \times \exp \left[ 0.1837\ln(p/e) \right]^2 \\
\times \exp \left[ 0.0775\ln(x/w) \right]^2 \times \exp \left[ 0.0869\ln(W/w) \right]^2 \\
\times \exp \left[ 0.2413\ln(g/e) \right]^2 \\
f = 1.3601Re^{-0.434} \times (p/e)^{-0.7032} \times (e/D_h)^{0.0863} \\
\times (e/w)^{0.0229} \times (W/w)^{0.0058} \times (g/e)^{0.1436} \times (x/w)^{-1.3003} \\
\times \exp \left[ 0.0098\ln(W/w) \right]^2 \times \exp \left[ 0.1925\ln(p/e) \right]^2 \\
\times \exp \left[ -0.4762\ln(x/w) \right]^2 \times \exp \left[ -0.0556\ln(e/w) \right]^2 \\
\times \exp \left[ 0.0455\ln(g/e) \right]^2 \\
Nu = 8.532 \times 10^{-3}Re^{0.932} (e/D_h)^{0.175} (p/e)^{1.196} (a/60)^{-0.0239} \\
(g/e)^{-0.0708} (W/w)^{0.506} (G_d/L_s)^{-0.534} \exp \left[ -0.2805\ln(p/e) \right]^2 \\
\times \exp \left[ -0.0753\ln(W/w) \right]^2 \times \exp \left[ -0.1153\ln(a/60) \right]^2 \\
\times \exp \left[ -0.0663\ln(G_d/L_s) \right]^2 \times \exp \left[ -0.223\ln(g/e) \right]^2 \\
f = 3.1934Re^{-0.3151} (e/D_h)^{0.268} (a/60)^{0.195} (p/e)^{-0.7941} \\
(g/e)^{-0.1769} (W/w)^{0.1132} (G_d/L_s)^{0.0610} \exp \left[ 0.1486\ln(p/e) \right]^2 \\
\times \exp \left[ 0.0974\ln(W/w) \right]^2 \times \exp \left[ -0.1527\ln(a/60) \right]^2 \\
\times \exp \left[ -0.1065\ln(G_d/L_s) \right]^2 \times \exp \left[ -0.6349\ln(g/e) \right]^2 \\
\] |
| Kumar et al. [85] (2013)| Multi-V-ribs with gap          | \[                                |
| Saini and Saini [30] (2008)| Arc ribs                      | \[                                |
| Sethi et al. [31] (2012)| Dimple shape                   | \[                                |
| Yadav et al. [32] (2013)| Dimple ribs in arc arrangement | \[                                |
| Hans et al. [33] (2017)| Broken-arc rib                | \[                                |
| Ambade et al. [95] (2019)| L-shaped rib                   | \[                                |
| Gill et al. [97] (2021)| Hybrid rib                    | \[                                |
| Pandey et al. [34] (2016)| Multiarc ribs with gap         | \[                                |
Table 5. Cont.

| Investigators          | Roughness                  | Correlations                                                                 |
|------------------------|----------------------------|-------------------------------------------------------------------------------|
| Singh et al. [153] (2014) | Multiarc ribs              | $\text{Nu} = 1.564 \times 10^{-4} \text{Re}^{1.3343} (\epsilon/D_h)^{0.048} (a/90)^{-0.555} (\text{p} / c)^{0.572}$  |
|                        |                            | $\times \exp \left[-0.099 \left(\ln \left(\text{W} / w\right) \right)^2 \right] \times \exp \left[-0.272 \left(\ln (a/90) \right)^2 \right]$  |
|                        |                            | $\times \exp \left[-0.148 \left(\ln (p / c) \right)^2 \right]$  |
|                        |                            | $f = 0.063 \text{Re}^{-0.118} (\epsilon/D_h)^{0.102} (a/90)^{-0.023} (\text{p} / c)^{0.562}$  |
|                        |                            | $\times \exp \left[-0.013 \left(\ln (a/90) \right)^2 \right] \times \exp \left[-0.140 \left(\ln (p / c) \right)^2 \right]$  |
| Hasan et al. [103] (2021) | Multiarc dimple shape      | $\text{Nu} = 8.84 \times 10^{-6} \text{Re}^{0.0263} (\epsilon / D_h)^{0.72} (a/60)^{-0.087}$  |
|                        |                            | $\times \exp \left[2.43 \left(\ln \left(\text{W} / w\right) \right)^2 \right]$  |
|                        |                            | $\times \exp \left[-0.524 \left(\ln (p / c) \right)^2 \right]$  |
|                        |                            | $\times \left(\text{W} / w\right)^{-0.528}$  |
| Lanjewar et al. [36] (2011) | Continuous W-ribs         | $\text{Nu} = 0.0613 \text{Re}^{0.0917} (\epsilon / D_h)^{0.4487}$  |
|                        |                            | $\times \exp \left[-0.5307 \left(\ln (a/60) \right)^2 \right]$  |
|                        |                            | $f = 0.06182 \text{Re}^{-0.2545} (\epsilon / D_h)^{0.4682}$  |
|                        |                            | $\times \exp \left[-0.28 \left(\ln (a/60) \right)^2 \right]$  |
| Kumar et al. [38] (2009)  | Discrete W-ribs            | $\text{Nu} = 0.105 \text{Re}^{0.873} (\epsilon / D_h)^{0.453}$  |
|                        |                            | $\times \exp \left[-0.59 \left(\ln (a/60) \right)^2 \right]$  |
|                        |                            | $f = 5.86 \text{Re}^{-0.40} (\epsilon / D_h)^{0.081}$  |
|                        |                            | $\times \exp \left[-0.579 \left(\ln (a/60) \right)^2 \right]$  |
| Gawande et al. [39] (2016) | S-shaped rib               | $\text{Nu} = 0.032 (\text{p} / c)^{0.5487} \times \exp \left[-0.0014 \left(\ln (\text{p} / c)^2 \right) \right]$  |
|                        |                            | $f = 0.280 (\text{p} / c)^{0.0515} \times \exp \left[-0.0519 \left(\ln (\text{p} / c)^2 \right) \right]$  |
|                        |                            | $\times \exp \left[-0.1107 \left(\ln (\text{p} / c)^2 \right) \right]$  |
| Kumar et al. [98] (2016)  | S-shaped rib               | $\text{Nu} = 1.433 \times 10^{-4} \text{Re}^{1.2744} \times \exp \left[-0.0048 \left(\ln (\text{W} / w)^{0.2748} \right) \right]$  |
|                        |                            | $\times \exp \left[-0.1084 \left(\ln (\text{W} / w)^{2} \right) \right]$  |
|                        |                            | $f = 1.43 \times 10^{-1} \times \exp \left[-0.0424 \times \left(\ln (\text{W} / w)^{0.1424} \times \exp \left[-0.7653 \left(\ln (\text{p} / c)^2 \right) \right] \right.$  |
|                        |                            | $\times \exp \left[-0.3219 \left(\ln (\text{p} / c)^2 \right) \right] \times \exp \left[-1.2159 \left(\ln (\text{p} / c)^2 \right) \right]$  |
| Baissi et al. [108] (2019) | Delta-shaped tubulators    | $\text{Nu} = 0.5884 \text{Re}^{0.4793} (\text{P} / b)^{0.5943} (\text{P} / b)^{-0.3201}$  |
|                        |                            | $\times \exp \left[-0.5426 \left(\ln (\text{P} / b)^{2} \right) \right]$  |
|                        |                            | $f = 0.338 \text{Re}^{-0.0969} \times \exp \left[-1.2539 \left(\ln (\text{P} / b)^{2} \right) \right]$  |
|                        |                            | $\times \exp \left[-1.2275 \left(\ln (\text{P} / b)^{2} \right) \right]$  |
|                        |                            | $\times \exp \left[-0.81 \left(\ln (\text{W} / w)^{2} \right) \right]$  |
| Kumar and Layek [110] (2020) | Winglet turbulators        | $\text{Nu} = 2.1 \times 10^{-8} \text{Re}^{1.452} (\text{S} / c)^{1.244} (\text{d} / \text{D})^{-3.9} (\text{L} / c)^{0.992}$  |
|                        |                            | $\times \exp \left[-7.72 \left(\ln (\text{L} / c)^{2} \right) \right] \times \exp \left[-1.4 \left(\ln (\text{S} / c)^{2} \right) \right]$  |
|                        |                            | $\times \exp \left[-7.83 \left(\ln (\text{d} / \text{D})^{2} \right) \right]$  |
| Bhushan and Singh [41] (2011) | Protrusions                | $\text{Nu} = 0.090 \text{Re}^{3.1334} \times \exp \left[-0.8583 \left(\ln (\text{D} / \text{D})^{2} \right) \right]$  |
|                        |                            | $f = 2.32 \text{Re}^{-0.201} (\text{S} / c)^{-0.383} (\text{L} / c)^{-0.484}$  |
| Patel et al. [118] (2020)  | NACA 0040 profile rib      | $\text{Nu} = 0.0901 \text{Re}^{3.1334} \times \exp \left[-0.8583 \left(\ln (\text{D} / \text{D})^{2} \right) \right]$  |
|                        |                            | $f = 0.3244 \text{Re}^{1.5728} (\epsilon / D_h)^{5.6226} \times \exp \left[-0.943 \left(\ln (\text{D} / \text{D})^{2} \right) \right]$  |
|                        |                            | $\times \exp \left[-0.0875 \left(\ln (\text{Re})^{2} \right) \right]$  |
| Gabhane and Patil [119] (2017) | Multi-C-shape rib         | $\text{Nu} = 0.206 \text{Re}^{0.0808} (\epsilon / D_h)^{0.2756} (\epsilon / p)^{-0.0372}$  |
|                        |                            | $f = 0.912 \text{Re}^{-0.2607} (\epsilon / D_h)^{0.1127} (\epsilon / p)^{0.1484}$  |
Table 5. Cont.

| Investigators               | Roughness                        | Correlations                                                                 |
|-----------------------------|----------------------------------|-------------------------------------------------------------------------------|
| Kumar and Layek [123] (2019)| Twisted tape                     | \( \text{Nu} = 3 \times 10^{-10} \text{Re}^{0.043} \left( \frac{g}{e} \right)^{-0.17} \left( \frac{p}{e} \right)^{1.575} \left( \frac{a}{60} \right)^{-0.84} \times \exp \left[ -3.75 \left( \frac{a}{90} \right)^{2} \right] \times \exp \left[ -0.85 \left( \ln \left( \frac{p}{e} \right) \right)^{2} \right] \) |
| Bhagoria et al. [47] (2002) | Wedge-shaped rib                 | \( \text{Nu} = 1.89 \times 10^{-4} \left( \text{Re} \right)^{1.121} \left( \frac{e}{D_{h}} \right)^{0.426} \exp \left[ -0.71 \left( \ln \left( \frac{p}{e} \right) \right)^{2} \right] \) |
| Promvonge et al. [127] (2021)| Combination of V-shaped rib and delta groove | \( \text{Nu} = 1.48 \text{Re}^{0.537} \frac{\text{Pr}}{\text{Re}} \frac{\text{Pr}}{1.9 (e/H)^{0.126}} \) |
| Alfarawi et al. [137] (2017) | Hybrid rib                       | \( \text{Nu} = 10.12 (p/e)^{-0.307} \left( \text{Re} \right)^{-0.144} \) |
| Saini and Saini [43] (1997)  | Expanded metal mesh              | \( \text{Nu} = 4 \times 10^{-4} \left( \frac{e}{D_{h}} \right)^{0.625} (L/10e)^{2.66} \text{Re}^{1.22} (S/10e)^{2.22} \) |
| Karmare and Tikekar [44] (2007)| Metal grit                       | \( \text{Nu} = 2.4 \times 10^{-3} \left( \frac{e}{D_{h}} \right)^{0.42} \text{Re}^{1.9} \left( \frac{p}{e} \right)^{-0.27} \left( \frac{a}{90} \right)^{-0.146} \) |
| Layek et al. [48] (2007)     | Chamfered rib combined with groove| \( \text{Nu} = 0.00225 \left( \frac{e}{D_{h}} \right)^{0.52} \left( \frac{g}{p} \right)^{-1.21} \text{Re}^{0.21} \left( \frac{p}{e} \right)^{1.172} \times \exp \left[ -0.22 \left( \ln \left( \frac{p}{e} \right) \right)^{2} \right] \times \exp \left[ -0.46 \left( \ln \left( \frac{p}{e} \right) \right)^{2} \right] \) |

7. Methodology and Formation of MATLAB Code for Calculating Thermal Efficiency

The flow chart of calculations as per the MATLAB program for calculating the thermal efficiency and heat loss coefficient of the duct with artificial roughnesses/turbulators is shown in Figure 42.

![Flow chart](image-url)
Solar energy I is absorbed by the collector plate, which is further transferred to the working fluid as heat loss from the bottom, useful heat gain, heat loss from the top cover, and heat loss from the side edges. The energy loses to the surroundings by convection and radiation from the top glass cover. The ambient and absorber plate temperatures are Ta and Tp, respectively. The step-by-step procedure for calculating the thermal efficiency is given below.

Heat exchange between the top glass cover and absorber plate:

\[ q_{\text{loss},p1-c1} = h_{c,c1-p}(T_p - T_{c1}) + \frac{c(T_p^{2} - T_{c1}^{2})}{c - p} - 1 \]

\[ = (h_{c,c1-p} + h_{r,p-c1})(T_p - T_{c1}) \]  \hspace{1cm} (14)

where

\[ h_{r,p-c1} = \frac{\sigma(T_p^{2} + T_{c1}^{2})(T_p + T_{c1})}{\frac{1}{T_p} + \frac{1}{T_{c1}} - 1} \]  \hspace{1cm} (15)

Thermal resistance:

\[ R_1 = \frac{1}{(h_{c,c1-p} + h_{r,p-c1})} \]  \hspace{1cm} (16)

Convection coefficient of heat transfer between the top glass cover and the absorber plate:

\[ h_{c,c1-p} = \frac{Nu.k}{L} \]  \hspace{1cm} (17)

where the Nusselt number between the glass cover and the absorber plate is given as [154]:

\[ Nu = 1 + \left[ \left( RaCos\beta / 5830 \right)^{0.33} - 1 \right] \]

\[ + 1.44[1 - 1708/RaCos\beta]^+ \left\{ 1 - 1708(sin1.8.\beta)^{1.6} / RaCos\beta \right\} \]  \hspace{1cm} (18)

where the Rayleigh number:

\[ Ra = \frac{g.\beta'.(T_p - T_c).L^3}{v.\alpha} \]  \hspace{1cm} (19)

The air physical properties are taken as \( \alpha, \beta', \) and \( v \) at the mean temperature of the plate.

Radiation heat transfer coefficient:

\[ h_{r,c1-a} = \frac{c\epsilon(T_{c1} + T_s)(T_{c1}^{2} + T_{s}^{2})(T_{c1} - T_s)}{(T_{c1} - T_a)} \]  \hspace{1cm} (20)

Resistance to the surrounding:

\[ R_1 = \frac{1}{(h_{r,c1-a} + h_w)} \]  \hspace{1cm} (21)

Top loss coefficient:

\[ U_t = \frac{1}{(R_1 + R_2)} \]  \hspace{1cm} (22)

Heat loss from the absorber to the ambient through the top glass cover:

\[ q_{\text{loss}} = U_t(T_p - T_a) \]  \hspace{1cm} (23)
The overall heat loss must be equal to the energy exchange between the plates:

\[ q_{\text{loss}} = q_{\text{loss, p-cl}} = q_{\text{loss, c1-a}} \]  

(24)

The edge and back heat loss coefficient are calculated as:

\[ U_b = \frac{1}{(R_4)} = k_{\text{ins}} \frac{L}{T} \quad \text{and} \quad U_e = \frac{1}{(R_3)} = \frac{(UA)_{\text{edge}}}{A_c} \]  

(25)

Overall heat loss coefficient:

\[ U_o = U_t + U_b + U_e \]  

(26)

Useful heat gain to fluid [155]:

\[ Q_u = \left[ I(\tau a) - U_o(T_p - T_a) \right] A_c \]  

(27)

Thermal Efficiency of the collector:

\[ \eta_{th} = \frac{Q_u}{A_c I} = \left[ (\tau a) - \frac{U_o(T_p - T_a)}{I} \right] \]  

(28)

8. Thermal Performance of Roughened SAH

The rough surface enhances the heat transfer rate over the smooth surface because of disrupting of the viscous sublayer, flow separation, secondary flow generation, and reattachment of flow, which leads to the enhancement of the level of turbulence adjacent to the heated surface. Due to an increase in the level of turbulence, the dead zone reduces remarkably where the convective rate of heat transfer is low. The turbulence promoters also increase friction losses, which leads to higher power consumption in the pumping of air because of high-pressure drops due to a high level of turbulence [156]. A high level of heat transfer and a small value of friction losses are the basic need of a compact and design-efficient SAH. In this regard, Nu/Nus and THPP help to select an optimum value of distinct roughness parameters and different rib arrangement patterns. Nu/Nus and THPP are determined with the help of corresponding correlations of \( f \) and \( Nu \) as listed in Table 5.

Nu/Nus and THPP increase significantly with the increase in Re for all shapes and sizes of roughness geometries. The \( Nu/Nus \) and THPP of different types of roughness with respect to Re are shown in Figures 43 and 44, respectively. The values of \( Nu/Nu_s \) and THPP change from 0.75 to 14.20 and 0.39 to 5.58 in the Re range of 3000 to 24,000, respectively.

The least values of \( Nu/Nu_s \) are recognized for the metal grit type of roughness and the highest value in the case of staggered broken-arc hybrid-rib roughness. The least values of \( Nu/Nu_s \) and THPP increase from 1.1 to 1.3 times, and the corresponding increase in pumping power requirement ranges from 1.0 to 1.4 times.
The thermal efficiency of the SAH increases significantly with the increase in Re for all shapes and sizes of artificial roughness geometry. The thermal efficiencies of a distinct type of roughness with respect to Re and ΔT/I are shown in Figures 45 and 46, respectively. The value of thermal efficiency changes from 0.27 to 0.79. The least values of η are recognized for a twisted tape and delta-shaped vortex generator type of roughness and the highest value in the case of a staggered broken-arc hybrid rib. The multiple V-rib with gaps, continuous multi ribs, and multiarc ribs with a gap also show higher values of η.
9. Conclusions

An attempt has been made to study the thermal and friction characteristics of various artificial ribs/turbulators exploited in SAH ducts. The correlations of $Nu$ and the friction factor for various rib configurations have been presented, and the thermohydraulic performance parameters of various rib configurations have been compared for a similar range of Reynolds number. Based on the literature review carried out in this paper, the following conclusions have been drawn.
The shape and size of artificial roughness and their pattern of arrangements on the duct surface are the most important factors for the performance optimization of the SAH.

The thermohydraulic characteristics of a large number of rib geometries have been investigated by many researchers. For most of the rib roughness geometries, the optimum performance has been achieved at the following parameters: $p/e = 10$, $W/w = 6$, $\alpha = 60^\circ$, and $e/D_h = 0.043$.

THPP and thermal efficiency show the highest values in the case of staggered broken-arc type of hybrid rib and least values in the case of metal grit, twisted tape, and delta-shaped vortex generator type of roughness.

The multi-V and multiarc-shaped roughnesses show higher thermohydraulic performance over other roughness geometries. The introducing gaps in the limb of multi-V-ribs enhance the level of turbulence significantly.

The multi-V-shaped ribs show a higher value of the friction factor, and arc-shaped circular dimples show a lower value of the friction factor.

The broken-arc-shaped rib combined with a staggered-arc rib piece has better performance than broken-arc-shaped and arc-shaped rib roughness.

The creation of gaps in the continuous ribs has shown remarkable improvement in thermohydraulic performance over the continuous ribs. The improvement in $Nu$ due to the creation of gaps in the continuous ribs ranges from 1.1 to 1.3 times, and corresponding increase in pumping power requirement ranges from 1.0 to 1.4 times.

THPP shows higher values in the case of an S-shape rib, multi-V ribs, and arc-shaped roughnesses with gaps. However, the performance of an S-shaped rib is not considerable at low $Re$, but the performance increases remarkably with the increase in $Re$.

The arc arrangement of rib roughness shows lower value pressure losses over the V-shaped arrangement due to the curved nature of the induced secondary flow along with the roughness.

In general, higher roughnesses’ height has a higher Nusselt number; however, higher roughnesses’ height contributes to higher pressure drop. Therefore, the thermohydraulic performance of roughnesses needs to be optimized. In this regard, net effective efficiency is the best tool to analyze roughnesses. On the basis of net effective efficiency, a multiarc rib with gaps is found to be best around 79% in comparison with other rib configurations, which is recommended for overall better performance.

The work presented in this review paper was carried out as a convective heat transfer coefficient from the absorber plate. Apart from performance improvement by heat transfer enhancement, there is a tremendous scope to further increase the performance of the SAH by exploiting more advanced active methods, such as electrodynamics, jet spray, mechanical aid, surface vibration, and fluid vibration. Further, heat loss through a top glass cover needs to be minimized by optimizing the natural convection between the glass cover and the absorber or utilizing the vacuum between them. Additionally, the flow structure should be studied using flow visualization, such as PIV, LCT, and CFD, to achieve the optimum rib arrangement.

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Nomenclature

| Symbol | Title                                      | Unit     |
|--------|--------------------------------------------|----------|
| b      | Roughness width                            | m        |
| c      | Characteristic separation length           | m        |
| d’     | Diameter of dimples                        | m        |
| d/x    | Relative gap position                      | -        |
| dR     | Relative punched hole size                 | -        |
| D      | Pipe inside diameter (to base of ribs)     | m        |
| D_e    | Equivalent diameter of annulus (d_1 − d_2) | m        |
| D_h    | Hydraulic diameter of duct                 | m        |
| e      | Height of roughness element                | m        |
| e^+    | Roughness Reynolds number                  | -        |
| e/D_h  | Relative roughness height                  | -        |
| e/H    | Blockage ratio                             | -        |
| f_s    | Smooth surface friction factor             | -        |
| f      | Friction factor of roughened surface       | -        |
| F_R    | Heat removal factor                        | -        |
| g      | Roughness function of heat transfer        | -        |
| g/e    | Relative gap width                         | -        |
| H      | Duct height                                | m        |
| I      | Insolation                                 | W/m²     |
| L      | Length of test section                     | m        |
| Nu     | Nusselt number                             | -        |
| N_g    | Number of gaps on half arc                 | -        |
| p/g    | Relative pitch-to-gap ratio               | -        |
| p’/p   | Relative staggered rib pitch               | -        |
| p/H    | Rib-pitch-to-channel-height ratio          | -        |
| P_L/b  | Relative longitudinal length of obstacles  | -        |
| P_L/e  | Relative transversal length of obstacles   | -        |
| P_R    | Relative winglet pitch                     | -        |
| Q_u    | Heat gain                                  | W        |
| Q_e    | Heat transfer function                      | -        |
| r/e    | Relative staggered rib size                | -        |
| R      | Momentum transfer roughness function       | -        |
| Ra     | Rayleigh number                            | -        |
| Re     | Reynolds number                            | -        |
| S      | Short way length between dimples           | m        |
| s’/s   | Relative gap position                      | -        |
| St     | Stanton number                             | -        |
| T_a    | Ambient temperature                        | K        |
| T_i    | Air inlet temperature                      | K        |
| T_f    | Mean air temperature                       | K        |
| T_p    | Plate temperature                          | K        |
| T_w    | Wall temperature                           | K        |
| ΔP     | Pressure drops                             | N/m²     |
| U_O    | Overall heat loss coefficient              | W/m²·K   |
| V      | Velocity of air in the SAH duct            | m/s      |
| w/e    | Staggered rib length to rib height         | -        |
| W/e    | Width-to-height ratio                      | -        |
| W/H    | Width-to-duct-height ratio                 | -        |
| W/w    | Relative roughness width                   | -        |
| W_1/w  | Relative gap position                      | -        |
| x      | Distance from starting                     | m        |
| η      | Thermohydraulic performance parameter      | -        |
| η_th   | Thermal efficiency of solar collectors     | -        |
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Symbols

- P: Density kg/m³
- ψ: Temperature factor T_w/T_i
- α: Angle of attack degree
- α': Arc angle degree
- α/90: Relative arc angle
- φ: Chamfering angle of rib degree
- β: Slope degree
- β': Thermal expansion coefficient of air 1/K
- εg: Glass cover emissivity
- εp: Absorber plate emissivity
- ν: Kinematic viscosity m²/s
- τ: Transmissivity
- σ: Stefan–Boltzmann constant W/m²·K⁴

P Density kg/m³
ψ Temperature factor T_w/T_i
α Angle of attack degree
α' Arc angle degree
α/90 Relative arc angle
φ Chamfering angle of rib degree
β Slope degree
β' Thermal expansion coefficient of air 1/K
εg Glass cover emissivity
εp Absorber plate emissivity
ν Kinematic viscosity m²/s
τ Transmissivity
σ Stefan–Boltzmann constant W/m²·K⁴
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