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# Solar Air Heater with Enhanced Surface: A Brief Overview

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**ABSTRACT—**

The solar air heater stands out as the most affordable and widely utilized solar energy collection device, serving various purposes such as drying agricultural products, heating spaces, seasoning timber, and curing industrial products. Incorporating artificial roughness on a surface proves to be an effective technique for boosting heat transfer rates in the duct of a solar air heater. Research on the use of artificial roughness in solar air heaters has been ongoing for the past thirty years. This article aims to provide a comprehensive overview of various roughness geometries employed for creating artificial roughness in solar air heaters, focusing on performance enhancement through experimental approaches. The article discusses thirty-eight experimental studies conducted on solar air heaters, each utilizing different roughness geometries. Notably, the literature lacks a comprehensive comparative study to assess the relative performance of various types of artificially roughened solar air heaters.

***Index Terms— Solar Air Heater, Heat transfer, Pressure Drop, CFD.***

## I. INTRODUCTION

Energy is the primary force in the universe, defining Earth's biomes and sustaining life. All forms of life, from single-celled microbes to blue whales, engage in a continuous process of consuming, using, and storing energy. Generally, energy represents a system's ability to cause external impacts, such as a force applied over a distance. The input or output of work changes the energy content of a body.

The solar air heater is a fundamental device that converts solar energy into thermal energy. Its primary applications include space heating, seasoning timber, and curing industrial products. Additionally, solar air heaters can effectively facilitate the curing/drying of concrete and clay building components. Despite its simple design and low maintenance requirements, the solar air heater faces challenges with a low heat transfer coefficient between the absorber plate and air, leading to reduced thermal efficiency.

This inefficiency stems from a low convective heat transfer coefficient between the flowing air and absorber plate (heat-transferring surface). This is attributed to the formation of a thin laminar viscous sub-layer on the absorber plate. To enhance the efficiency of the solar air heater, modifications to the boundary layer developed on the heated surface are necessary (refer to Fig. 1).

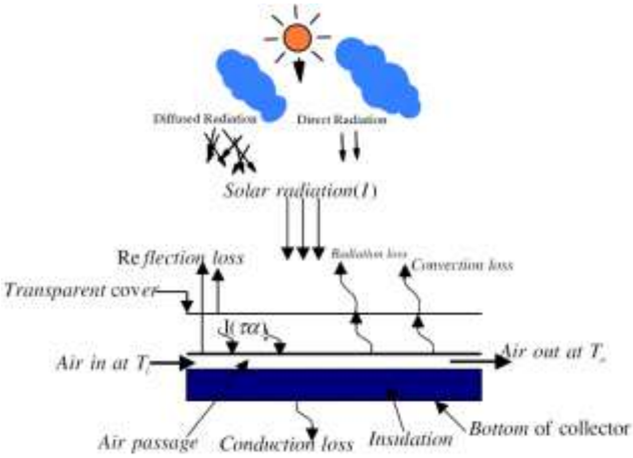


**Fig. 1.** Solar air heater

One well-known method for modifying the boundary layer involves creating artificial roughness on the heat transfer surface, typically in the form of repeated ribs, grooves, or a combination of both. This technique is widely used in various applications such as cooling gas turbine blades, nuclear reactors, and solar air heating systems. The introduction of artificial roughness disrupts the laminar viscous sub-layer, generating local wall turbulence through flow separation and reattachment between consecutive ribs. This disruption reduces thermal resistance, leading to increased heat transfer and improved efficiency. However, this enhancement comes at the expense of a higher friction factor and power penalty.

Researchers continually focus on selecting the optimal shape and arrangement of artificial roughness to modify the boundary layer, enhance the heat transfer coefficient, and minimize pressure drop (power penalty). Therefore, it is essential to review different types of artificial roughness applied to heat transfer surfaces and examine their impact on the heat transfer coefficient (Nusselt number) and friction factor.

The concept of artificial roughness was initially introduced by Joule [1] to boost heat transfer coefficients in in-tube steam condensation. Since then, numerous experimental investigations have explored the application of artificial roughness in various areas, including the cooling of gas turbines, electronic equipment, nuclear reactors, and compact heat exchangers (Fig. 1).

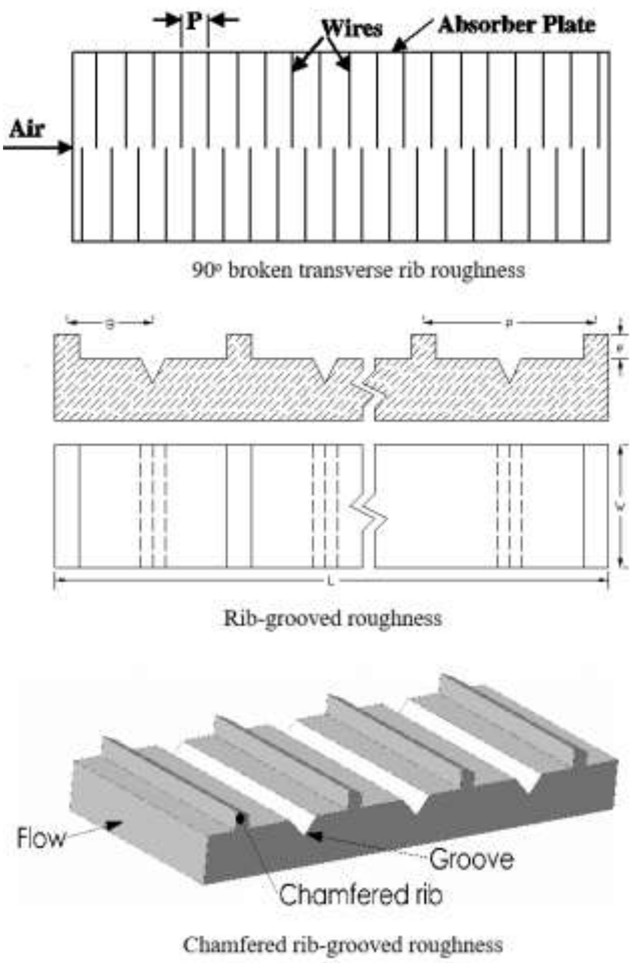


**Fig. 2.** Different geometries

Nunner [2] was the first to develop a flow model and compared it to the temperature profile in smooth tube flow with an increased Prandtl number. The proposed model predicts that roughness reduces the thermal resistance in the turbulence-dominated wall region without significantly affecting the viscous region. This argument was quantified by using the Prandtl analogy and replacing Pr with (f/fs)Pr. The model suggests that the value of St/Sts decreases with an increase in the Prandtl number. It also predicts that St/Sts is independent of the roughness type. Nikuradse [3] developed a friction correlation for flow over sand-grain roughness based on the law of the wall similarity. Using a heat-momentum transfer analogy relation, Dipprey and Sabersky [4] achieved excellent correlation of their data for flow in a sand-grain roughened tube.

The concept proposed by Dipprey and Sabersky, applicable to any roughness where the law of the wall similarity holds, led to further investigations. Prasad and Mullick [5] were the first to introduce the application of artificial roughness, in the form of small diameter wires attached to the underside of the absorber plate, to improve the thermal performance of a solar air heater for drying purposes. Subsequent to their work, various experimental investigations on solar air heaters involving roughness elements of different shapes, sizes, and orientations with respect to flow direction have been carried out to optimize the arrangement of roughness element geometry [6-9]. The thermo-hydraulic performance of artificially roughened solar air heaters, considering various parameters, can be obtained through a CFD approach [10-19].

The aim of the present study is to review the effect of various turbulator geometries on the flow and heat transfer through the rectangular channel. The key dimensionless geometrical parameters used to characterize artificial roughness include relative roughness pitch (P/e), relative roughness height (e/D), angle of attack (α), and aspect ratio, where aspect ratio is the ratio of duct width to duct height, playing a crucial role in investigating thermo-hydraulic performance.

## APPLICATION OF ARTIFICIAL ROUGHNESS IN SOLAR AIR HEATER

Ahn [20] studied five types of roughness elements in a rectangular duct with parameters e/DH = 0.0476, P/e = 8, and W/H = 2.33. They aimed to compare the thermo-hydraulic performance of these elements, concluding that triangular ribs exhibit the highest heat transfer capacity. The Nusselt number is greater for square and triangular ribs compared to semicircular ribs, with square ribs having the highest friction factor.

Chandra et al. [21] explored the impact of varying the number of transverse ribbed walls in a square channel with parameters Re = 10,000 to 80,000, P/e = 8, e/DH = 0.0625, and L/Dh = 20 for fully turbulent flow. They observed a heat transfer increase with one ribbed wall and noted improvements with additional ribbed walls. The friction factor showed a maximum increase with four-sided ribbed walls and a minimum with one ribbed wall.

Tanda [22] investigated heat transfer coefficient distribution in a rectangular channel with transverse continuous, transverse broken, and V-shaped broken ribs. Liquid crystal thermography revealed optimal performance for continuous transverse ribs, 45 V-shaped ribs, and 60 V-shaped ribs at P/e = 13.3. Transverse broken ribs with P/e = 4 and 8 provided higher heat transfer augmentation, while transverse continuous ribs with P/e = 4 and 8 showed lesser heat transfer increment.

Andallib et al. [23] examined heat transfer and flow characteristics in the entrance section of a rectangular channel with one and two solid ribs at the bottom surface. Various parameters, including Re = 2.09 x 10^4 and P/e = 10, were considered. Experimental and theoretical results aligned, indicating similar performance within the selected data range.

Won and Ligrani [24] compared thermo-physical characteristics in channels with parallel and cross rib turbulators on two opposite surfaces. Nusselt numbers were similar for crossed and parallel ribs, but local Nusselt number for parallel ribs was significantly higher. Pressure loss was higher in the central part of the channel.

Wang and Sunden [25] investigated heat transfer and fluid flow in a rectangular channel with broken V-shaped up ribs using crystal thermography and particle image velocimetry. They found that heat transfer performance was higher than continuous ribs but with increased friction loss.

Liu et al. [26] explored heat transfer increment in a solar air heater with an absorber plate roughened by extended surfaces geometry.

Prasad and Mullick [27] investigated a solar air heater with protruding wires on the underside of the absorber plate, observing a 9% improvement in plate efficiency for a Reynolds number of 40,000. Cross corrugated sheet with protruding wires outperformed plane galvanized iron sheet, showing a 44.5% higher plate efficiency (Fig. 3).

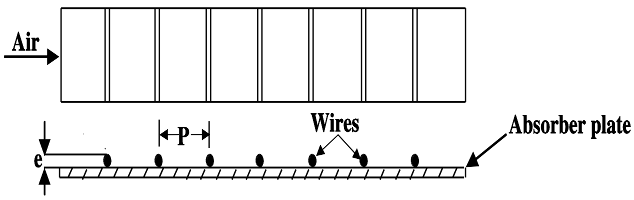


**Fig. 3.** Circular rib geometries

Gupta, Solanki, and Saini [28] investigated the thermo-physical effects of transverse wire roughness on the absorber plate's heat and fluid flow characteristics in the transitionally rough flow region (5 < e+ < 70) for rectangular solar air heater ducts. The parameters considered were Reynolds number (Re) ranging from 3000 to 18000, duct aspect ratio (W/H) from 6.8 to 11.5, relative roughness height (e/D) from 0.018 to 0.052, and relative roughness pitch (P/e) of 10. They observed that heat transfer increased up to 1.8 times compared to smooth solar air heaters at α = 60, and the friction factor increased by 2.7 at α = 70 within the investigated parameter range.

Saini and Saini [29] investigated fully turbulent flow with expanded metal mesh as an artificial roughness element. They used a rectangular duct with W/H = 11, relative longways length (L/e) from 25 to 71.87, relative short way length (S/e) of 15, and e/D ranging from 0.012 to 0.039 for Reynolds number (Re) from 1900 to 13000. Their findings indicated that maximum values of Nusselt number and friction factor occurred at an angle of attack of 61.9 and 72, respectively. They also developed correlations for Nusselt number and friction factor.

Gupta et al. [30] focused on the optimum design and operating conditions in artificially roughened solar air heaters. The investigated parameters included e/D (0.023 to 0.05), Re (4000 to 18000), solar intensity (I) of 400 to 1300 W/m2, and α = 60. Optimum design conditions were determined, and a correlation for Reynolds number was developed based on the selected investigation parameters.

Ekkad and Han [31] explored a two-pass square channel solar air heater with rib tabulators, considering parameters like Re (6000 to 60000), e/DH (0.125), P/e (10), and α (90 parallel, 60 parallel, 60 V, and 60 broken V shaped ribs). Their investigation covered thermo-physical characteristics and secondary flow in various regions, concluding that Nusselt number ratios in the second pass were 2 to 3 times higher than in the first pass. They found that 60 parallel, 60 V, and 60 broken V ribs provided different heat transfer characteristics in different sections of the channel.

Verma and Prasad [32] studied optimal performance parameters for artificially roughened solar air heaters. They considered Re (5000 to 20000), m (0.01 to 0.06 Kg/sec), P/e (10 to 40), e/D (0.01 to 0.03), and e+ (8 to 42). They identified the optimal value of e+ opt = 24, at which ηthermal = 71%, signifying a significant increase in heat transfer using artificial roughness.

Singh et al. [33] investigated the heat and fluid flow characteristics of a solar air heater with discrete V down ribs as roughness elements, considering parameters such as Re (3000 to 15000), relative gap width (g/e) from 0.5 to 2, relative gap position (d/w) from 0.20 to 0.80, P/e (4 to 8), α (30 to 75), and e/Dh (0.015 to 0.043). They developed correlations for Nu and f within the specified parameter range, with maximum increases of 3.04 in Nusselt number and 3.11 in friction factor at the optimum values of parameters.

Momin et al. [34] investigated the effect of V-shaped ribs as roughness elements on the underside of the absorber plate of a solar air heater. They considered parameters Re (2500 to 18000), e/DH (0.02–0.034), α (30 to 90), p/e (10), and W/H (10.15). They observed increases in heat transfer and friction of 2.30 and 2.83, respectively, compared to a smooth duct at α = 60. In comparison to inclined ribs, the enhancement was 1.14, and correlations for Nusselt number and friction factor for the V-shaped ribs were developed.

Karwa [35] investigated the thermo-physical behavior of a roughened solar air heater with transverse, inclined, V continuous, and V discrete ribs at α = 60 for inclined and V patterns. Parameters included Re (2800 to 15000) and R (e+) (17 to 90). Heat transfer and friction factor correlations were developed based on the law of wall similarity and heat momentum transfer analogy. Significant increases in heat transfer and friction factor were observed for the various rib configurations.

Sahu and Bhagoria [36] explored the heat transfer coefficient in a solar air heater using 90 broken integral transverse ribs on the absorber plate. Parameters considered were W/H (8), Re (3000 to 12000), P/e (6.67, 13.33, 20), e/D (0.0338), and I (750–880 W/m2). They concluded that maximum heat transfer and efficiency (83.5%) occurred at P/e = 1.33, with a considerable increment in heat transfer and friction factor.

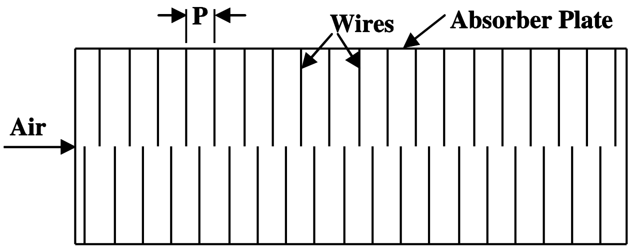


**Fig. 4.** $90^{o}$ broken transverse rib roughness

Jaurker et al. [37] explored the thermo-physical characteristics of rib-grooved artificial roughness in a rectangular solar air heater duct, considering parameters such as Re = 3000 to 21,000; e/D = 0.0181–0.0363; P/e = 4.5–10; and relative groove position ratio (g/p) = 0.3 to 0.7. They developed correlations for Nusselt number and friction factor based on their investigation. The conclusion drawn was that for a rib-grooved duct with P/e = 6.0 and g/p = 0.4, the maximum Nusselt number is 2.75. Additionally, with P/e = 6.0, g/p = 0.4, e/D = 0.0363, the maximum friction factor is 3.61.

Mittal et al. [38] studied the impact of various types of roughness elements on the absorber plate of a solar air heater, incorporating parameters like W/H = 10; e/D = 0.02 to 0.04; P/e = 10; and Re = 2000 to 24000. They aimed to determine the effective efficiency using correlations for heat transfer and friction factor developed by different researchers within the specified parameter range. The findings suggested that inclined ribs with low e/D values exhibit high effective efficiency for Re > 12000. Furthermore, expanded metal mesh demonstrates better effective efficiency for Re < 12000, and the effective efficiency of a smooth solar air heater surpasses that of solar air heaters with roughness at very high Reynolds numbers.

Karmare and Tikekar [39] investigated the impact of a solar air heater roughened with metal grit ribs, considering parameters like e/Dh = 0.035 to 0.044; P/e = 12.5–36; relative length of grit (l/s) = 1.72 to 1; and Re = 4000 to 17000. They developed correlations for Nusselt number and friction factor within the specified parameter range. The study concluded that the optimal values for parameters within the selected range are l/s = 1.72, e/Dh = 0.044, P/e = 17.5, which results in optimum performance (Fig.5).

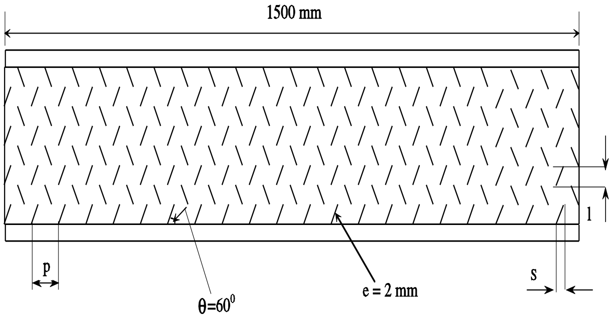


**Fig. 5.** Metal grit rib roughness

In his experiments on flow through pipes, Webb et al. [40] utilized a wide range of e/Dh ratios with P/e values exceeding 10. The ribs were aligned normal to the main stream direction. Firth and Mayer [41] explored the heat transfer and friction factor performance of artificially roughened surfaces in a gas-cooled reactor, including square transverse rib, helical rib, trapezoidal transverse ribs, and three-dimensional surfaces. The experiments involved roughness on one, two, and four walls of the absorber plate, with a preference for roughness on one wall within the range of Re = 3000 to 30000.

Various investigators developed different correlations for heat transfer and friction factor based on their experiments. Bhargava and Rizzi [42] demonstrated that increasing the channel depth along the length of solar air heaters improves efficiency. Adel A. Hegazy R. [43] optimized the channel height of different types of solar air heaters. J. C. Han, L. R. Glicksman, and W. M. Rohsenow [44] investigated the effects of rib shape, angle of attack, and pitch to height ratio on friction factor and heat transfer on symmetric and staggered ribs. They concluded that ribs at a 45-degree attack angle outperform those at a 90-degree angle and sand grain roughness.

In another study, J. C. Han and J. S. Park [45] examined the combined effects of rib, angle-of-attack (α = 90, 60, 45, and 30), and channel aspect ratio (W/H = 1, 2, and 4) on the heat transfer coefficient in short rectangular channels (L/D = 10 and 15) with two opposite rib-roughened walls. They found that the highest heat transfer and pressure drop occurred at α = 60' in the square channel and α = 90 with W/H = 4 in the rectangular channel.

Shou-shing Hsieh et al. [46] investigated the effects of aspect ratio (W/H) = 1, 2, Reynolds number (Nu) 63.5 < Re < 254, and the initial boundary layer thickness on low-speed forced convective heat transfer near two-dimensional transverse ribs. They derived correlations for average Nusselt number. Ying-Jong Hong et al. [47] explored turbulent flow on staggered ribs in a square duct with two opposite rib-roughened walls. They established temperature distribution and correlations between Nusselt number and Reynolds number. The heat transfer rate was calculated to be 2.02-4.60 times higher than fully developed turbulent flow in a smooth duct for Re = 13000.

Jenn-Jiang Hwang and Tong-Miin Liou [48] investigated the thermo-hydraulic performance of a low aspect ratio channel with staggered slit ribs on top and bottom walls. They concluded that the arrangement of ribs provides higher heat transfer enhancement with lower pressure drop for the same solid rib height and spacing. Additionally, friction factor decreases with an increase in rib open area ratio.

Xiufang Gao and Bengt Sunden [49] studied heat transfer and pressure drop in a rectangular duct with staggered ribs, considering parameters like aspect ratio (W/H) = 1 to 8, relative roughness height (e/DH) = 0.06, angle of attack (α) = 60, and Reynolds number (Re) = 1000 to 6000. They observed span-wise variation of heat transfer coefficient along the rib length due to secondary flow, with reattachment occurring between two ribs. The V downstream ribs induced the highest friction factor, followed by V upstream and parallel ribs.

Akira Murata and Sadanari Mochizuki [50] investigated laminar and turbulent flow with transverse or angled rib turbulators in a square channel. They concluded that heat transfer is highest in front of the rib, and laminar flow has a lesser effect on the flow field with ribs than turbulent flow.

S. W. Ahn [51] explored five different types of roughness elements in a rectangular duct to understand the comparative thermo-hydraulic performance. They concluded that triangular ribs have the highest heat transfer capacity, with square and triangular ribs outperforming semicircular ribs. Square ribs, however, have the highest friction factor.

P.R. Chandra et al. [52] investigated the effect of varying the number of ribbed walls with transverse ribbed walls for fully turbulent flow in a square channel. They concluded that one ribbed wall provides a 40% improvement in heat transfer for Re = 12,000 to 75,000. The maximum increase in friction factor was found with four-sided ribbed walls, and the minimum with one ribbed wall.

Giovanni Tanda [53] studied heat transfer coefficient distribution in a rectangular channel with transverse continuous, transverse broken, and V-shaped broken ribs. Liquid crystal thermography was applied, revealing that continuous transverse ribs, 450 V-shaped ribs, and 600 V-shaped ribs exhibited the maximum performance. Transverse broken ribs with P/e = 4 and 13.3 gave the best thermal performance.

Andallib Tariq et al. [54] investigated the heat transfer and flow characteristics in the entrance section of a rectangular channel with one and two solid ribs at the bottom surface. They utilized hot wire anemometry (HWA), resistance thermometry (RTD), and liquid crystal thermography (LCT) and found similar performance under the given range of data selected in comparison to theoretical energy balance.

S.Y. Won and P.M. Ligrani [55] compared the thermo-physical characteristics in channels with parallel and cross rib turbulators on two opposite surfaces. They found that Nusselt number is almost the same for crossed and parallel ribs, with local Nusselt number for parallel ribs significantly higher than crossed ribs. Pressure loss is higher in the central part of the channel.

Lieke Wang and Bengt Sunden [56] investigated heat transfer and fluid flow in a rectangular channel with broken V-shaped up ribs. They used crystal thermography (LCT) and particle image velocimetry (PIV) techniques, concluding that the performance in heat transfer is higher than continuous ribs with more friction loss.

Several other types of turbulator elements have been extensively used to improve heat transfer characteristics [57-85].

## CONCLUSION

This article presents a detailed review of the experimental investigations carried out by various researchers in order to enhance the heat transfer by the use of artificial roughness of different shapes, sizes and orientations. The effects of various rib parameters on heat transfer and fluid flow processes are discussed in detail. Heat transfer and friction factor correlations reported in literature are also presented in tabular form. These correlations may be used to predict the thermal as well as hydraulic performance of solar air heaters having roughened ducts. In this article a comparative study is also carried out to select best roughness element geometry for maximum convective heat transfer with minimum pumping losses. The conclusion can be summarized as follows:

1. The use of artificial roughness on a surface is an effective technique to enhance heat transfer to fluid flowing in the duct. Artificially roughened solar air heaters have enhanced rate of heat transfer as compared to the smooth solar air heaters under the same geometric/ operating conditions.
2. It has been found that roughness geometries being used in solar air heaters are of many types depending upon shapes, size, arrangement and orientations of roughness elements on the absorber plate.
3. There are several parameters that characterize the roughness elements, but for solar air heater the most preferred roughness geometry is repeated rib type, which is described by the dimensionless parameters viz. relative roughness height (e/D), relative roughness pitch, (P/e), angle of attack ($\alpha$) and channel aspect Ratio (W/H) etc.
4. Transverse rib roughness enhances the heat transfer coefficient by flow separation and generation of vortices on the upstream and downstream of rib and reattachment of flow in the inter-rib spaces.
5. It can be concluded that the use of artificial roughness results in higher friction and hence higher pumping power requirements. It is desirable that design of solar air heater should be made in such a way that it should transfer maximum heat energy to the flowing fluid with minimum consumption of blower energy.
6. It is found that among the entire roughness elements investigated, the multi-V-shaped rib roughness with gap has the highest Nusselt number as compared to other roughness geometries for the investigated range of parameters.
7. It is found that among the entire roughness elements investigated, the multi-V-shaped rib roughness with gap has the highest friction factor as compared to other roughness geometries for the investigated range of parameters.
8. It is found that among the entire roughness elements investigated, arc shaped rib geometry has the highest thermohydraulic performance parameter as compared to other roughness geometries for the investigated range of parameters.

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