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Thermal Performance Enhancement of Solar Air Heaters Using Artificial Roughness: A Comprehensive Review

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Abstract

Solar air heaters (SAHs) are among the most common devices for converting solar energy into heat, yet their thermal efficiency is often low due to the poor heat transfer characteristics between the absorber plate and the air. Artificial roughness on the absorber plate is a promising technique for enhancing heat transfer by breaking the laminar sub-layer and creating turbulence. This paper presents a comprehensive review of various roughness geometries, including V-shaped ribs, chamfered ribs, metal grit ribs, and others, focusing on their influence on Nusselt number (Nu), friction factor (f), and overall thermo-hydraulic performance. A detailed comparison of these geometries highlights their effectiveness in different operating conditions. The paper also discusses the optimization of roughness geometry to balance heat transfer enhancement and the associated pressure drop penalty. Finally, the review identifies future research opportunities to improve the performance of solar air heaters further.

Keywords: Solar Air Heater, Artificial Roughness, Nusselt Number, Friction Factor, Heat Transfer, Thermo-Hydraulic Performance

1 Introduction

With the rapid depletion of fossil fuels and increasing concerns over climate change, renewable energy sources are becoming essential for sustainable development. Among these sources, solar energy stands out for its abundance and potential to meet growing energy demands. Solar air heaters (SAHs) are simple devices that harness solar energy to heat air, which can be used for applications such as space heating, crop drying, timber seasoning, and industrial processes. Despite their widespread use, SAHs suffer from inherently low thermal efficiency. This inefficiency arises from the low thermal conductivity of air and the presence of a laminar sub-layer that forms on the absorber plate, which restricts the heat transfer from the plate to the air.

To address this issue, various methods have been proposed to enhance the convective heat transfer in SAHs. Among them, the introduction of *artificial roughness* on the absorber plate is one of the most effective and economically viable solutions. Artificial roughness creates turbulence in the air flowing over the absorber plate, which disrupts the laminar sub-layer and increases the heat transfer rate. However, the induced turbulence also leads to an increase in the *friction factor (f)*, resulting in a higher pressure drop and increased energy consumption for airflow. Therefore, optimizing the roughness geometry is critical to maximizing the heat transfer enhancement while minimizing the increase in friction.

The objective of this paper is to review the various types of artificial roughness used in SAHs and evaluate their impact on thermal performance. The focus will be on roughness geometries such as V-shaped ribs, chamfered ribs, metal grit ribs, and others. The paper will also discuss the parameters that influence the performance of these roughness geometries, such as the *relative roughness height (e/D)*, *relative roughness pitch (p/e)*, and *angle of attack (α)*. Finally, the review will highlight future research directions for further improving the thermal efficiency of solar air heaters.

2 Literature Review

2.1 Solar Air Heaters

Solar air heaters have been used for decades due to their simplicity and low cost. The basic design consists of an absorber plate that captures solar radiation and transfers the heat to air flowing over or under the plate. The heated air is then used for various applications, such as space heating or drying agricultural products. However, the thermal performance of SAHs is limited by the low convective heat transfer coefficient between the air and the absorber plate, especially in laminar flow conditions. To improve the efficiency of SAHs, researchers have explored different techniques for enhancing heat transfer, including the use of extended surfaces (fins), jet impingement, and artificial roughness.

2.2 Heat Transfer Enhancement with Artificial Roughness

The concept of artificial roughness was introduced to increase turbulence in the airflow over the absorber plate, thereby enhancing the heat transfer coefficient. This method involves adding small roughness elements to the absorber plate, such as ribs, wires, or grit particles, to disrupt the laminar sub-layer and promote turbulent mixing. The effectiveness of artificial roughness in enhancing heat transfer depends on the size, shape, and orientation of the roughness elements, as well as the Reynolds number of the airflow.

2.3 Previous Studies on Artificial Roughness Geometries

Several researchers have investigated different roughness geometries for enhancing heat transfer in SAHs. Momin et al. [1] studied the effect of V-shaped ribs on the thermal performance of SAHs and found that the Nusselt number increased by a factor of 2.30 compared to smooth ducts. Karwa et al. [2] investigated the use of chamfered ribs and reported a 10-40% improvement in thermal efficiency. Karmare and Tikekar [3] explored the use of metal grit ribs and observed a 35% increase in thermal efficiency, although this was accompanied by a significant increase in the friction factor. Other researchers have examined the performance of ribs with different shapes, such as W-shaped ribs, broken transverse ribs, and combined inclined and transverse ribs [7, 8].

3 Methodology

3.1 Concept of Artificial Roughness

Artificial roughness is applied to the absorber plate of a solar air heater to increase the heat transfer rate by creating turbulence in the airflow. The roughness elements are designed to disrupt the laminar sub-layer that forms near the surface of the plate, which increases the convective heat transfer coefficient. However, this increased turbulence also leads to a higher friction factor, which results in a greater pressure drop and higher energy consumption for airflow.

The key parameters that influence the performance of artificial roughness are:

- **Relative Roughness Height (e/D):** The ratio of the height of the roughness elements to the hydraulic diameter of the air passage. A higher relative roughness height generally leads to greater heat transfer but also increases the friction factor.

- **Relative Roughness Pitch (p/e):** The ratio of the distance between two consecutive roughness elements to the height of the roughness elements. A smaller pitch leads to more frequent turbulence generation but may increase the pressure drop.

- **Angle of Attack (α):** The angle at which the roughness elements are inclined relative to the direction of airflow. The angle of attack affects the generation of secondary flows, which can enhance heat transfer.

3.2 Performance Metrics

The performance of solar air heaters with artificial roughness is evaluated using the following metrics:

- **Nusselt Number (Nu):** The Nusselt number is a dimensionless quantity that represents the enhancement of convective heat transfer. A higher Nusselt number indicates greater heat transfer.

- **Friction Factor (f):** The friction factor quantifies the resistance to airflow caused by the roughness elements. A higher friction factor leads to a greater pressure drop and increased energy consumption for airflow.

- **Thermo-Hydraulic Performance (THP):** The thermo-hydraulic performance is a measure of the overall efficiency of the solar air heater, taking into account both the heat transfer enhancement and the increase in pumping power.

4 Types of Artificial Roughness

4.1 V-Shaped Ribs

V-shaped ribs are one of the most effective roughness geometries for enhancing heat transfer in SAHs. The V-shape creates secondary flows that increase turbulence and improve heat transfer. Momin et al. [1] conducted experiments on SAHs with V-shaped ribs and found that the Nusselt number increased by 2.30 times compared to smooth ducts. The friction factor also increased by 2.83 times, but the overall thermo-hydraulic performance was favorable. The optimal angle of attack for V-shaped ribs was found to be 60°, as shown in Figure 1 from [1].

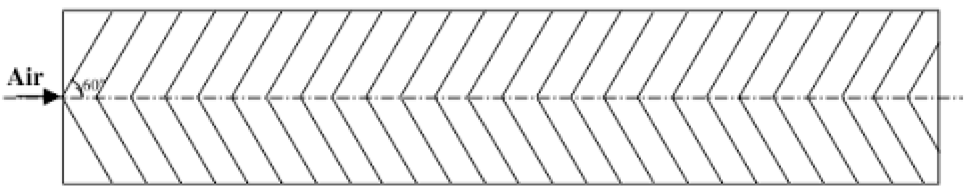

Fig. 1. V-shaped ribs at 60° angle of attack.

4.2 Chamfered Ribs

Chamfered ribs provide a good balance between heat transfer enhancement and pressure drop. Karwa et al. [2] studied the use of chamfered ribs in SAHs and reported a 10-40%increase in thermal efficiency. The friction factor increased by 80-290%, but the ribs were particularly effective at low Reynolds numbers. Chamfered ribs disrupt the laminar sub-layer and create localized turbulence, enhancing heat transfer without excessively increasing the pressure drop. Figure 2 from [2] illustrates the chamfered rib geometry.

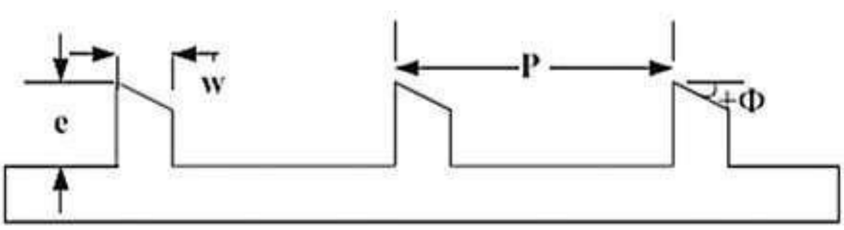

Fig. 2. Illustration of Chamfered Rib Configuration

4.3 Metal Grit Ribs

Metal grit ribs are small roughness elements that create a high level of turbulence, leading to substantial heat transfer enhancement. Karmare and Tikekar [3] investigated the use of metal grit ribs in SAHs and found a 35% increase in thermal efficiency. However, the friction factor increased by 2-3 times, particularly at higher Reynolds numbers. Metal grit ribs are most effective in applications where high heat transfer rates are required, as shown in Figure 3 from [3].

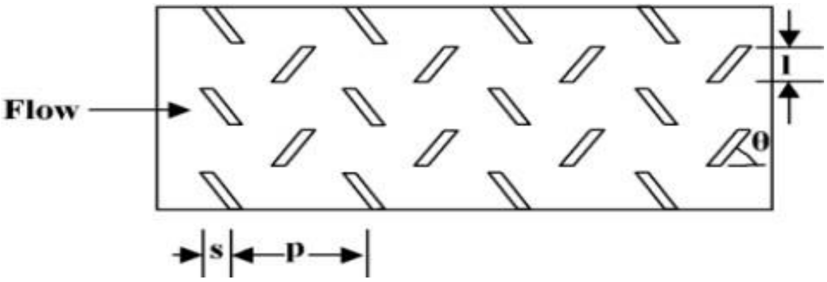

Fig. 3. Schematic Representation of Metal Grit Ribs Configuration

4.4 W-Shaped Ribs

W-shaped ribs have been shown to significantly improve the heat transfer characteristics of SAHs. Lanjewar et al. [7] studied the performance of W-shaped ribs and found that the Nusselt number increased by 32-92%, depending on the angle of attack. The friction factor also increased, but the overall thermo-hydraulic performance was favorable. W-shaped ribs are particularly effective at an angle of attack of 60°, as shown in Figure 4 from [7].

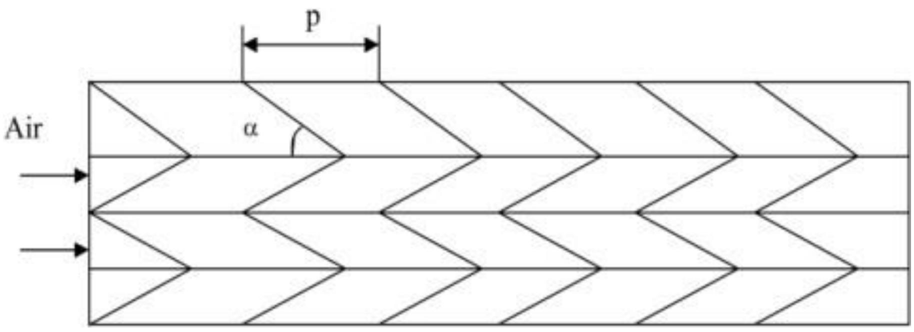

Fig. 4. Schematic of W-Shaped Ribs Configuration

4.5 Other Roughness Geometries

In addition to the roughness geometries discussed above, several other types of artificial roughness have been studied. These include broken transverse ribs, rib-grooved roughness [14], and combined inclined and transverse ribs [8]. Each of these geometries has been shown to enhance heat transfer, but the increase in friction factor varies depending on the specific design. For example, Sahu and Bhagoria [4] studied the use of broken transverse ribs and found that the Nusselt number increased significantly, but the friction factor also increased sharply.

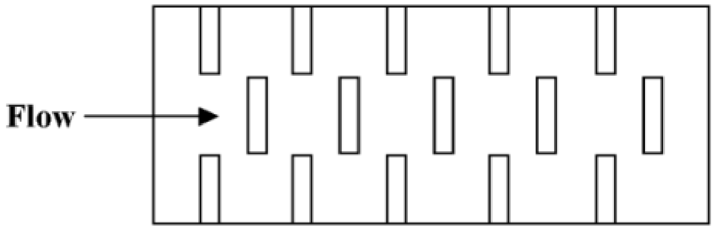

Fig. 5. Schematic of Broken Transverse Ribs Configuration

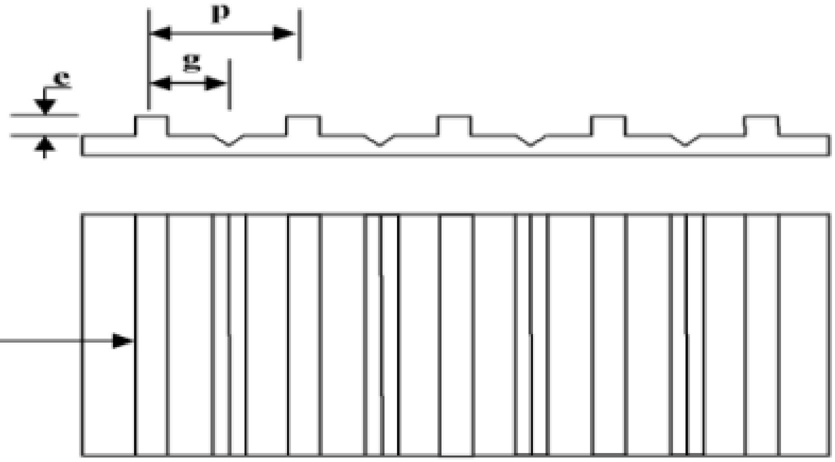

Fig. 6. Schematic of Rib-grooved Roughness Configuration

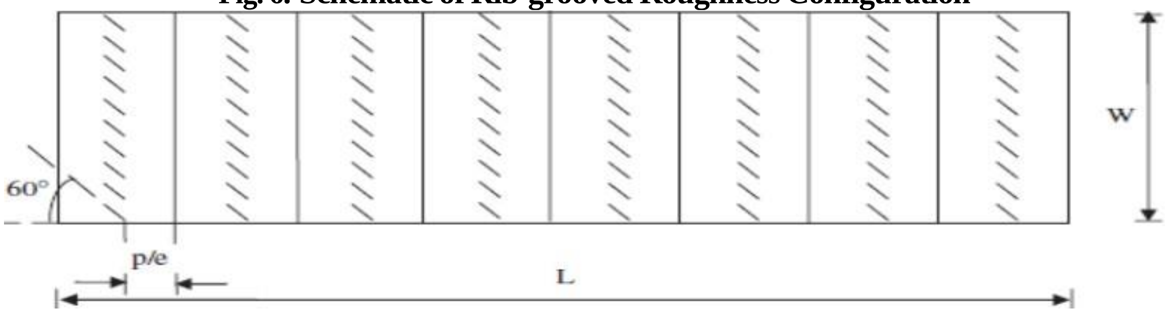

Fig. 7. Schematic of Combined Inclined and Transverse Rib Roughness Configuration

5 Results and Discussion

5.1 Comparative Analysis of Roughness Geometries

Table 1. Comparison of Roughness Geometries and Their Performance

Roughness Geometry	Nusselt Number Increase	Friction Factor Increase	Optimal Angle of Attack
V-Shaped Ribs	2.30 times	2.83 times	60°
Chamfered Ribs	10-40%	80-290%	15°
Metal Grit Ribs	35%	2-3 times	-
W-Shaped Ribs	32-92%	1.39-1.57 times	60°

Broken Transverse Ribs	1.80-2.50 times	2.40-3.00 times	90°

5.2 Discussion on Performance Trade-Offs

The data show that V-shaped ribs provide the highest overall performance, with a significant enhancement in heat transfer and a moderate increase in the friction factor. Chamfered ribs are also effective, particularly in low-flow applications where the Reynolds number is low. Metal grit ribs [3] offer substantial heat transfer enhancement but come with a high pressure drop penalty, making them suitable for applications requiring high heat transfer rates. W-shaped ribs provide a good balance between heat transfer and friction factor, especially at an angle of attack of 60°.

Table 2. Angle of Attack (α) for Maximum Value of Heat Transfer Coefficient for Different Types of Artificial Roughness

Investigators	Roughness Geometry	Value of (α) for Maximum Heat Transfer Coefficient
Abdul-Malik Ebrahim Momin, J.S. Saini, S.C. Solanki (2001)	V-shaped rib roughness	60°
J.L. Bhagoria, J.S. Saini, S.C. Solanki (2001)	Transverse wedge shape	90°
M.M. Sahu, J.L. Bhagoria (2005)	90° broken transverse rib	90°
K.R. Aharwal, B.K. Gandhi, J.S. Saini (2007)	Gap in inclined continuous rib	60°
S.V. Karmare, A.N. Tikekar (2008)	Metal rib grits roughness	60°
Apurba Layek, J.S. Saini, S.C. Solanki (2008)	Transverse chamfered rib-groove	60°
S.K. Saini, R.P. Saini (2008)	Arc-shaped wire ($\alpha/90$ = 0.3333)	-
Thakur Sanjay Kumar, Vijay Mittal, N.S. Thakur, Anoop Gautum (2011)	60° inclined continuous discrete rib	60°
Sachin Choudhary, Varun, Manish Kumar Chouhan (2012)	Continuous M-shaped ribs turbulators	60°
A.M. Lanjewar, J.L. Bhagoria, R.M. Sarviya (2012)	W-shaped	60°

6 Applications of Solar Air Heaters

Solar air heaters are widely used in various applications, including:

- **Space Heating:** Solar air heaters can be used to heat residential and commercial buildings, reducing the need for conventional heating systems and lowering energy costs.
- **Crop Drying:** SAHs are commonly used in agricultural applications to dry crops, such as fruits, vegetables, and grains. The use of SAHs for crop drying can reduce post-harvest losses and improve the quality of dried products.
- **Timber Seasoning:** Solar air heaters are used in the timber industry to season wood, reducing the moisture content and improving the quality of the finished product.
- **Industrial Processes:** SAHs can be used in various industrial processes that require low to moderate temperatures, such as drying [9], curing, and preheating.

7 Future Research Directions

While significant progress has been made in improving the thermal performance of solar air heaters through the use of artificial roughness, several areas of research remain unexplored. Future research could focus on the following areas:

- **Optimization of Roughness Geometry:** Further studies are needed to optimize the size, shape, and orientation of roughness elements for different operating conditions. Computational fluid dynamics (CFD) simulations could be used to explore new roughness geometries and evaluate their performance [6].
- **Hybrid Roughness Designs:** Combining multiple roughness geometries, such as V-shaped and chamfered ribs, could lead to improved performance. Experimental and numerical studies should be conducted to evaluate the potential of hybrid designs.
- **Advanced Materials:** The use of advanced materials with higher thermal conductivity could enhance the heat transfer performance of SAHs. Research should explore the use of materials such as nanomaterials and phase change materials in SAHs.
- **Integration with Other Renewable Technologies:** SAHs could be integrated with other renewable energy technologies, such as photovoltaic panels or thermal storage systems, to improve overall system efficiency.

8 Conclusion

1. This paper provides an overview of various studies aimed at improving heat transfer through the implementation of artificial roughness.

2. Artificially roughened surfaces with diverse geometries (shape, size, orientation) are identified as an effective method for improving heat transfer rates while minimizing friction penalties.

3. Researchers primarily recommend rib and wire matrix roughness to enhance thermal performance, with rib roughness being the most effective.

4. The paper includes correlations developed for heat transfer and friction factors specific to solar air heater ducts with various artificial roughness geometries.

5. These correlations can be utilized to predict the thermal efficiency, effective efficiency, and hydraulic performance of solar air heater ducts with artificial roughening.

References

[1] Momin, A.-M.E., Saini, J.S., & Solanki, S.C. (2001). Heat transfer and friction in solar air heater ducts with V-shaped rib roughness on absorber plate. *International Journal of Heat and Mass Transfer*, 45(16), 3383-3396.

[2] Karwa, R., Solanki, S.C., & Saini, J.S. (2000). Thermo-hydraulic performance of solar air heaters having integral chamfered rib-groove roughness on absorber plates. *Energy*, 26, 161-176.

[3] Karmare, S.V., & Tikekar, A.N. (2008). Heat transfer and friction factor correlation for artificially roughened ducts with metal grit ribs. *Solar Energy*, 83, 6-13.

[4] Sahu, M.M., & Bhagoria, J.L. (2005). Augmentation of heat transfer coefficient by using 90° broken transverse ribs on absorber plate of solar air heater. *Renewable Energy*, 30(13), 2057-2073.

[5] Layek, A., Saini, J.S., & Solanki, S.C. (2008). Heat transfer and friction characteristics for artificially roughened ducts with compound turbulators. *Renewable Energy*, 34(6), 1292-1298.

[6] Eiamsa-ard, S., & Promvonge, P. (2008). Numerical study on heat transfer of turbulent channel flow over periodic grooves. *International Communications in Heat and Mass Transfer*, 35, 844-852.

[7] Lanjewar, A.M., Bhagoria, J.L., & Sarviya, R.M. (2012). Thermo-hydraulic performance of solar air collector using W-shaped artificial roughness. *Journal of Environ- mental Research and Development*, 6(3A), 908-910.

[8] Varun, Saini, R.P., & Singal, S.K. (2007). Investigation of thermal performance of solar air heater having roughness elements as a combination of inclined and transverse ribs on

absorber plate. *Renewable Energy*, 33(6), 1398-1405.

[9] Prasad, K., & Mullick, S.C. (1983). Heat transfer characteristics of a solar air heater used for drying purposes. *Applied Energy*, 13(2), 83-93.

[10] Karmare, S.V., & Tikekar, A.N. (2007). Thermo-hydraulic performance of roughened solar air heaters. *International Journal of Heat and Mass Transfer*, 50(17), 4342-4351.

[11] Saini, S.K., & Saini, R.P. (2008). Development of correlations for Nusselt number and friction factor for solar air heater with roughened duct having arc-shaped wire as artificial roughness. *Solar Energy*, 82(12), 1118-1130.

[12] Chaube, A., Sahoo, P.K., & Solanki, S.C. (2006). Analysis of heat transfer augmenta- tion due to rib roughness over absorber plate of a solar air heater. *Renewable Energy*, 31(3), 317-331.

[13] Kumar, S., & Saini, R.P. (2009). CFD-based performance analysis of a solar air heater duct provided with artificial roughness. *Renewable Energy*, 34(6), 1285-1291.

[14] Jaurker, A.R., Saini, J.S., & Gandhi, B.K. (2005). Heat transfer coefficient and friction characteristics of rectangular solar air heater duct using rib-grooved artificial roughness. *Solar Energy*, 80(8), 895-907.

[15] Thakur, N.S., Mittal, V., & Gautum, A. (2011). Heat transfer and friction factor correlations for rectangular solar air heater duct having 60° inclined continuous discrete rib arrangement. *British Journal of Applied Science & Technology*, 1(3), 67-93.

[16] Smith, Eiamsa-ard, & Pongjet, P. (2012). Heat transfer characteristics using artificial roughness of 60° M-shaped ribs turbulators in a solar air heater. *International Journal of Energy and Environment*, 3(1), 33-48.

[17] Gupta, D., & Kaushik, S.C. (2005). Exergy analysis and investigation for a solar air heater with roughened absorbers. *Renewable Energy*, 30(5), 683-699.

[18] Karwa, R. (2003). Experimental studies of augmented heat transfer and friction in asymmetrically heated rectangular ducts with ribs on the heated wall in transverse, inclined, and V-continuous patterns. *Applied Thermal Engineering*, 23(6), 707-719.

[19] Kumar, A., Bhagoria, J.L., & Sarviya, R.M. (2009). Heat transfer enhancement in a rectangular duct with ribbed roughness in solar air heater. *Renewable Energy*, 33(7), 1436-1444.