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Improvement in the efficiency of solar air heater using artificial roughness: A review on CFD approach

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Abstract
Solar air heaters are the flat plate collectors used for a variety of purposes to heat water and air respectively. Comparing solar water heaters to solar air heaters, the former are often smaller, less costly and simpler. Because of the sluggish rate of heat transfer between the absorber plate and the air moving through the duct, it is common to assume that a solar air heater has a low thermal efficiency. The heat transfer rate needs to be increased in order to increase thermal efficiency, which will make a solar air heater a more efficient solar energy utilization system. In solar air heaters, artificial roughness significantly affects the friction factor and heat transmission coefficient. Before conducting real experiments, several scientists carried out a number of computer simulations to examine the effects of different artificial roughness types, locations, and heights within solar air heater ducts across a broad range of parameters. Real-world applications can utilize optimal data provided by computational fluid dynamics (CFD) analysis. In current work, the artificial roughened duct with computational fluid dynamics approach employed by several researchers is described.

Keywords: Solar air heater, computational fluid dynamics, artificial roughness, heat transfer

Introduction

The need for various energy sources has grown in tandem with global industrialization and economic expansion. expanding worldwide population and expanding material demands have both contributed to a rise in the pace of energy consumption. Environmental dangers and the world's depleting fossil fuel supplies have spurred the development of renewable energy sources. Among the many possibilities available to meet the continually increasing need for energy, solar energy is the most promising long-term resource. It is thought to be the most promising renewable energy source due to its immense potential. Free and limitless solar energy is used as a non-polluting fuel source. The simplest method of using solar energy for heating is to convert it into thermal energy using solar collectors. Solar water heaters and solar air heaters, which are often used to heat water and air, respectively, employ flat plate collectors. Solar air heaters are important components of solar thermal systems because of their minimal material and cost requirements. Solar air heaters are typically believed to have lower thermal efficiency due to the absorber plate's restricted rate of heat transfer capabilities and the air flowing through the duct. Several researchers have also looked at the use of artificial roughness to boost the heat transfer coefficient using computational fluid dynamics (CFD). The present paper presents the CFD approaches adopted by different authors and their respective results

Different concepts of artificial roughness

Saxena *et al.* [1] yielded the main elements of a system for using solar energy was a solar air heater (SAH) as shown in Fig. 1. At the absorbing surface, these air heaters capture the light, transform it into thermal energy, and then transfer that energy to a fluid passing through the collector. SAHs were the most common and affordable, gathering tools because to their innate simplicity. SAHs are used in a variety of solar energy applications, particularly drying agricultural products, seasoning wood, and room heating. from research had shown that every component of a solar air heater—including the absorber tray, ducting, glazing, insulation, extended surfaces, and tilt angle—significantly affects the system's thermal performance. They focused on the developments that was followed round the globe in various aspects of solar air heating systems since 1877 up to now, with a glimpse of some novel patents of SAHs. The various methods that were used to improve the thermal performance of SAHs such as; optimizing the dimensions of the air heater construction elements, use of extended surfaces with different shapes and dimensions, use of sensible or latent storage media, use of concentrators to augment the available solar radiation, integrating photovoltaic elements with the heaters, etc.

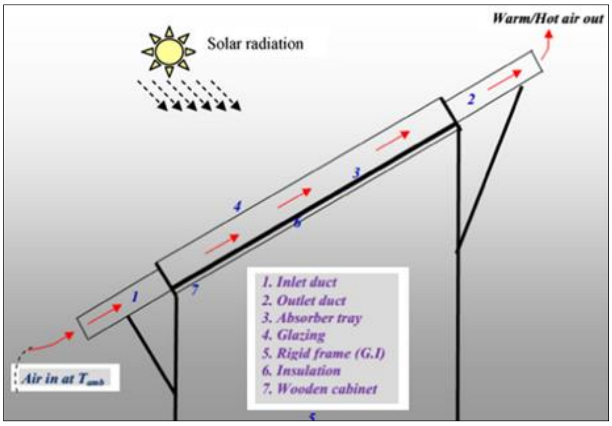

Fig 1: Major components of solar air heater [8]

Abbasov *et al.* [2] showed the possibility of using a solar drying installation as shown in the Fig. 2 to save thermal or electric energy spent on drying transformer windings. The efficiency of the collector and the solar dryer could be improved by using metal shavings with a diameter of 0.01 meters, placed 0.3 meters apart from each other and attached to the walls of a smooth blackened metal she*et al.*ong the main direction of the airflow. Biondi *et al*. [3] explained how the performances of conventional solar air heaters could be based upon two parameters, specific air flow rate (G) and geometric coefficient (K)—by assuming fully developed turbulent flow, rectangular ducts,

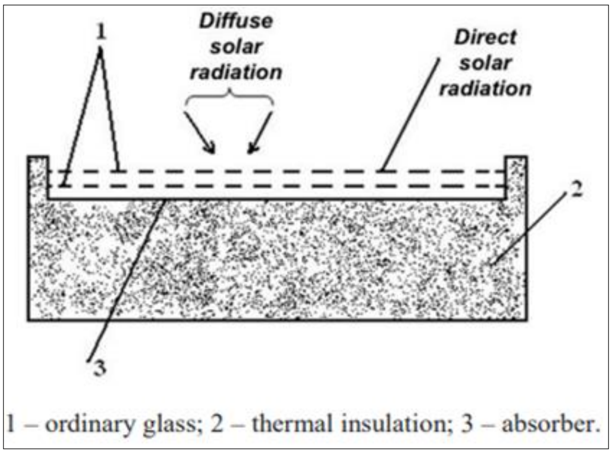

Fig 2: Flat plate collector [2].

and identical conditions regarding construction typology, environmental parameters, material choice, and inlet temperature. In the hypotheses, the geometric coefficient of the collector (K) could be utilized in experimental tests to group air heaters with similar geometries. For collectors of type D, the formula published for UL (assuming equal temperatures for the air above and below the absorber) facilitated easy computation through the zero-capacitance model. The provided diagram shown in the Fig. 3 proved useful for both comparing the performances of various collector types and selecting the construction type that best satisfied specific usage conditions. Bhargava *et al*. [4] explained how the fluid must be circulated using electrical energy. The electrical energy generated by a hybrid system, which combines thermal and photovoltaic systems, is enough to turn the pump. The photovoltaic cells are adhered directly to the plate absorber. A portion of the solar radiation that misses the cell area is captured by the airflow and transformed into electrical energy. Thus, a hybrid system runs entirely on solar radiation. Authors analysed a hybrid system, which combines a photovoltaic system and an air heater.
For various solar cell sizes, the ideal area required to produce enough electrical energy for the pump is estimated. A linear relation used to calculate the variation of efficiency of the solar cells with temperature. It was shown that the hybrid system is self-sufficient only for certain design parameters and flow rates.

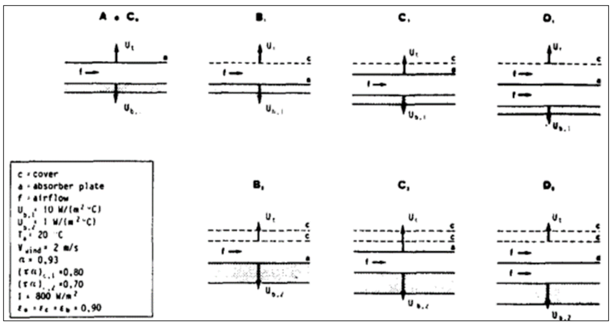

Fig 3: Design of the solar air heater duct [3]

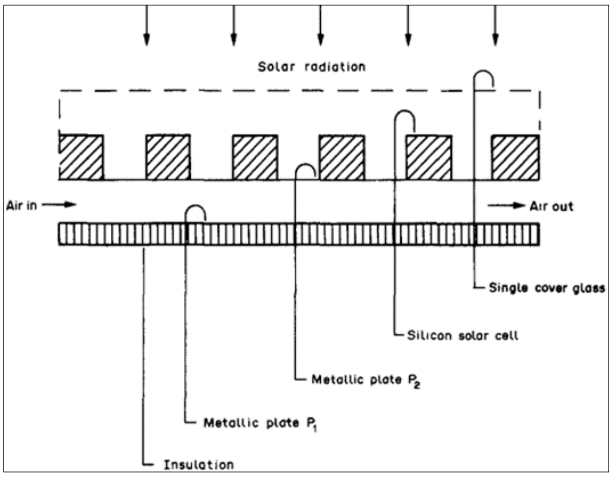

Fig 4: Photovoltaic thermal solar collector (hybrid solar collector) [5]

Duct with a single broad wall that has transverse chamfered rib-groove roughness on repeat as shown in the Fig. 4. Heat transfer and fluid friction are both impacted by roughness parameters, such as relative roughness pitch Layek *et al*. [5] Observed that under identical operating conditions, solar air heaters with artificial roughening outperform those with plane surfaces. Even so, added artificial roughness raises the fluid pressure even further, which boosts pumping power. A numerical study is conducted on the generation of entropy in a solar air heater P/e, relative roughness height e/Dh, relative groove position g/P, chamfer angle f, and flow Reynolds number Re. Roughness designs that are reasonably optimized are found, and the generation of entropy is minimized. Aharwal *et al*. [6] suggested that adding artificial roughness to a solar air heater duct was great way to improve the heat transfer from the absorber plate to the air. The experimental study on heat transmission and friction properties of solar air heater ducts with integrated, repeating, discrete square ribs on the absorber plate was presented as shown in the Fig. 5. Investigated that conducted into the impact of geometrical features, particularly the gap width and gap position.

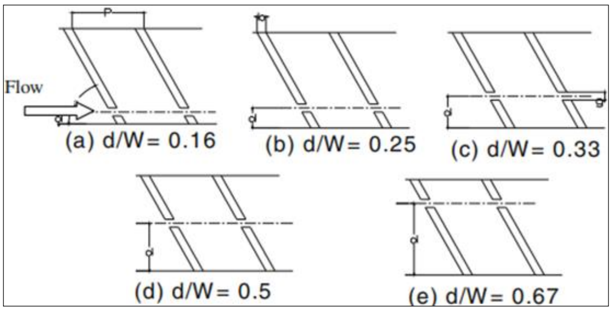

Fig. 5: Roughness geometry of discrete square ribs [6]

The width to height ratio (W/H) of the roughened duct is 5.83. The experiment involved varying the relative gap position (d/W) and relative gap width (g/e) from 0.16 to 0.5 and 0.5–2.0, respectively.
Experiments with the relative roughness pitch (P/e) have been conducted for the Reynolds number range of 3000 to 18,000. range of 4–10; relative roughness height (e/D) range of 0.018–0.037; and angle of attack (a) range of 30–90. The optimum values of parameters for rib arrangement have been obtained and discussed. For Nusselt number, the

maximum enhancement of the order of 2.83 times of the corresponding value of the smooth duct has been obtained, however, the friction factor has also been seen increase by 3.60 times of that of the smooth duct. The maximum enhancement is observed at a relative gap position of 0.25 for relative gap width of 1.0, relative roughness pitch of 8.0, angle of attack of 60 and relative roughness height of 0.037. Based on the experimental data, correlations for Nusselt number and friction factor have been developed as function of roughness parameters of inclined discrete square ribs and flow Reynolds number.

Bhushan and Singh [7] studied that heat transfer and friction characteristics of artificially roughened duct of solar air heaters. Methodology of artificial roughness and experimental studies carried out by various investigators observed that artificial roughness is a good technique to improve thermal performance of solar air heaters.

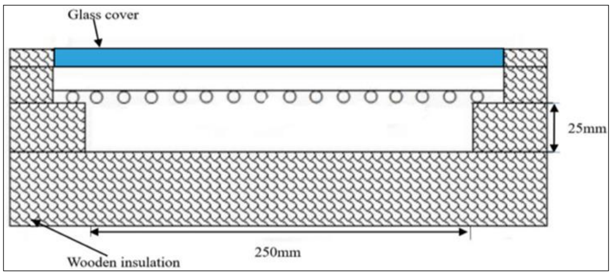

Fig 6: Artificially roughened duct [9]

Gill *et al.* [8] designed, manufactured, and tested two inexpensive solar air heaters: a single-glazed model and a double-glazed. To lower the cost of manufacture, thermocole, ultraviolet-stabilized plastic sheet, etc. were employed in the process. These were simultaneously evaluated in the summer and winter, under load and without it. In addition to a packed bed solar air heater that absorbs radiation utilizing iron chips. The beginning expenditures of a packed bed solar air heater with the same aperture area are 26.8% and 22.8% for single- and double-glazed units, respectively. It was discovered that the maximum stagnation temperatures of a single-glazed and double-glazed solar air heater were 43.5 °C and 62.5 °C, respectively, on a given day with no load. The effectiveness of individual the solar air heaters' efficiency with single, double, and packed beds, which correspond to a flow rate of 0.02 m3 /s-m2, were, in the winter, 30.29%, 45.05%, and 71.68%, in that order. For three solar air heaters, the collector efficiency factor, heat removal factor based on air outlet temperature, and air inlet temperature were also calculated. Kumar [9] explained how the active viscous laminar sub-layer on the surface of the absorber limits the heat transmission coefficient of solar air heaters (SAHs). In order to eliminate the viscous sub-layer that forms beneath the SAH duct's absorber surface, artificial roughness was introduced as shown in the Fig. 6. An experimental study was conducted to compare the Nu and f enhancement of rough ducts to smooth ones using a unique roughness geometry multi-v-pattern convex protrusion planted on an absorber as shown in the Fig. Re range 2500–18,500, relative protrusion width (Wd/Wv) 1, 2, 3, 4, and 5, relative protrusion height (e/Dh) = 0.03, relative protrusion pitch (p/e) = 10, relative print diameter (e/d) = 0.5, α = 60º, and W/H = 12 were all taken into consideration for the experiment. The purpose of the inquiry is to determine the ideal roughness geometrical parameter among investigated values. Results for thermal and thermohydraulic performance parameters have also been worked out and reported. The key findings in the present work were compared with single and multi v roughness in rib shapes. The findings were conclusive and worth evaluating. The maximum Nusselt number and friction is obtained corresponding to Wd/Wv = 4 and 5, respectively. The maximum thermal efficiency is 66% obtained at Wd/Wv = 4, p/e = 10, and e/Dh = 0.03. The maximum THPP is observed to be 3.29 at Re = 13000

CFD simulation of solar air heater ducts

Kumar and Saini [10] worked on computational fluid dynamics (CFD) used to analyze the performance of a solar air heater duct that has artificial roughness in the form of thin circular wire in arc-shaped geometry as shown in the Fig. 7. The impact of arc-shaped geometry on friction factor, heat transfer coefficient, and A range of working parameters (Reynolds number, Re from 6000 to 18,000 and solar radiation of 1000 W/m^2) and roughness parameters (relative roughness height (e/D) from 0.0299 to 0.0426 and relative roughness angle (a/90) from 0.333 to 0.666) were examined in order to improve performance. The investigation was conducted using various turbulence models, and the outcomes are contrasted. Based on data that have been determined to be in good agreement, the Renormalization-Group (RNG) k-3 model is utilized to predict heat transfer and friction factor in the duct. The overall enhancement ratio has been calculated in order to discuss the overall effect of the roughness and working parameters. A maximum value of overall enhancement ratio has been found to be as 1.7 for the range of parameters investigated. Gupta and Kaushik [11] Examined that using roughened geometry in the solar air heater duct increases efficiency. For extremely high values of Re, the roughened geometries should be used, according to the η_{ef} based criterion. The η_{II} based. The criterion indicates that when Re is very high, the η_{II} may be negative or the energy required for the pump to operate may be greater than the energy used by the solar air heater to collect heat. As a result, η_{II} offers the relevant performance evaluation criterion. Over the complete range of Re, no particular roughened geometry provides the highest energetic performance. Roughened design should produce greater turbulence in solar air heater ducts with bigger flow cross-section areas and low Re; smooth surfaces, circular ribs, and V-shaped ribs work well in smaller flow cross-section area of solar air heater duct and high Re.

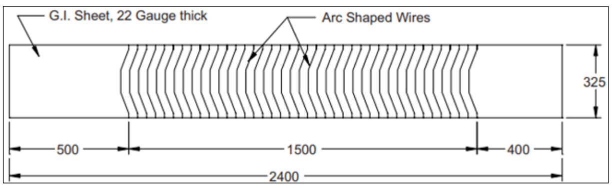

Fig 7: Arc shaped ribs on the inner side of the absorber plate [10]

Thakur *et al.* [12] examined that artificial roughness to the absorber plate's underside, the solar air heater's absorber plate's heat transfer coefficient to the air can be significantly raised. In order to improve the heat transfer coefficient of a solar air heater with a roughened air duct that has artificial roughness in the form of a discrete rib that is 60° inclined, an experimental study was conducted. Studies have also been done on the increase in friction factor that results from adding such an artificial roughness element. System parameters that have been studied on the Nusselt number (Nu) and friction factor (f) with relative gap width (g/e) 1 and Reynolds number (Re) varied from 4105 to 20526 include relative roughness height (e/D), relative roughness pitch (P/e), and relative gap position (d/W). With the help of this roughness element, the heat transfer coefficient has been significantly improved. For these solar air heaters, correlations for the Nusselt number and friction factor have also been developed using experimental data, and the predicted and experimental values of these parameters agree well. Chamoli *et al*. [13] observed that by increasing the rate of heat transfer, a solar air heater's thermal performance can be improved. With the idea of doubling the heat transfer area without raising the cost of the system, double pass solar air heaters have a higher thermal efficiency than single pass models. According to published research, the performance analysis of a double pass solar air heater equipped with heat transfer augmentation techniques—extended surfaces, packed beds, and corrugated absorbers—showed a greater increase in thermal efficiency when compared to a double duct solar air heater. includes heat transfer enhancement, flow phenomena, pressure drop in ducts, and double pass solar air heater design.

Kulkarni and Kim [14] conclude that the best shape for obstructions as shown in the Fig. 9 attached to a solar air heater was investigated using three-dimensional Reynolds-averaged Navier-Stokes analyses of fluid flow and

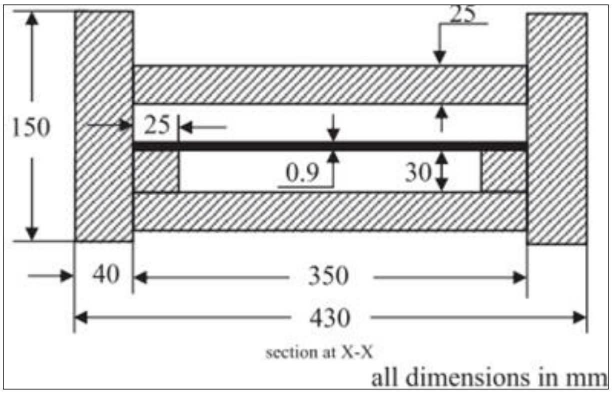

Fig 8: Cross section of solar air heater duct [12]

heat transmission. Based on the hydraulic diameter of the channel, the Reynolds number was between 6800 and 10,000. The thermal and aerodynamic characteristics of the solar air heater are determined by the Nusselt number and friction factor, respectively. Three different obstacle layouts as well as four distinct obstacle shapes—rectangular, trapezoidal, pentagonal, and U-shaped—were examined to see how they affected the solar air heater's effectiveness. The findings demonstrate that for every example examined, the performance factor—which was measured as the ratio of thermal to aerodynamic performance—was more than unity, and the pentagonal obstacle shape suggests the highest performance regardless of the Reynolds number. Detailed analyses of the thermal and flow fields are performed in order to obtain a better understanding of the heat transfer characteristics. Srivastav *et al*. [15] conducted a review to facilitate a discussion and evaluation of the findings obtained by researchers. It covered an overview of solar air heater technology, detailed descriptions of various types of solar air heaters, solar air heaters with different absorber plate surface geometries to enhance the rate of heat transfer. Different designs of solar air heaters with and without heat storage materials, especially phase change materials, were reported. The use of fins on the absorber plate and different surface geometries of the absorber plate enhanced the rate of heat transfer during sunshine hours, while the use of PCM (thermal energy storage medium) supplied heat energy during off sunshine hours. As a result, solar air heaters gained popularity in a wide range of applications.

Alam and Kim [16] examined that Using of protrusion rib roughness's on the solar air heater (SAH) (as shown in Fig. 10, duct's absorber plate can significantly increase the rate of heat transmission without sacrificing pressure drop. The numerical study of the SAH duct roughened with conical protrusion ribs was presented by Alam and Kim. For Reynolds numbers ranging from 4000 to 16000, the effects of relative rib height (0.020≤e/D≤0.044) and relative rib pitch (6≤p/e≤12) on Nusselt number and friction factor have been investigated.

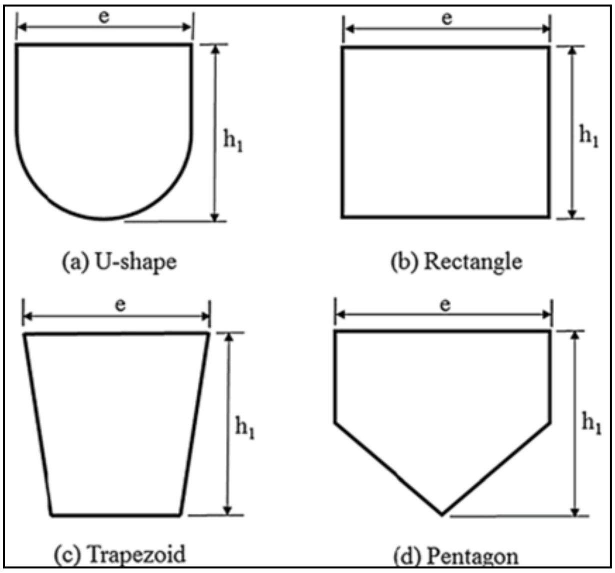

Fig 9: Shapes and arrangements of obstacle [14]

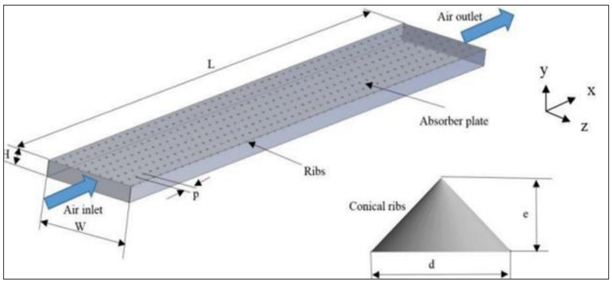

Fig 10: Computation fluid domain [16]

The useful energy gain to air and heat losses to the environment were used to calculate the roughened duct's thermal efficiency. The results showed that the efficiency enhancement factor (EEF) is 1.346 and the maximum thermal efficiency (η) is 69.8%. As a function of Reynolds number and roughness parameters, correlations between the friction factor and Nusselt number have also been established.

Parkash and Saini [17] worked on experimental investigation into the heat and fluid flow characteristics of solar air heater ducts that have been artificially roughened. A range of

Reynolds numbers (Re) from 2000 to 20000, relative roughness pitches (P/e) from 15 to 30, relative rib lengths (r/g) from 0.4 to 1.0, and relative rib pitches (Pr/P) from 0.2 to 0.8 were covered by the roughness and operating parameters. Relative roughness height (e/D), angle of attack (α), and relative roughness gap are the other parameters that remain constant. The results demonstrate that using a roughened surface has significantly improved the Nusselt number and thermohydraulic performance while increasing the friction factor Korpale *et al*. [18] examined that there are Various methods of surface modification have been employed to improve the heat transfer from solar air heater absorber plates. When designing heat transfer equipment, precise values for the design parameters must be within the operational window. The goal of the current work is to evaluate the maximum thermohydraulic performance of rectangular section ribs installed in solar air heaters by developing empirical correlations and taking into account all possible design combinations within the specified input parameter range. It is governed by the design of experiment algorithms, specifically with response surface methodology taking into account four input parameters: relative rib pitch, which ranges from5 to 60, relative rib height, which ranges from0.065 to 0.252, Reynolds number, which ranges from4000 to 20000, and relative rib width, which ranges from 4000 to 20000, relative rib height between 0.065 and 0.252, relative rib width between 0.5 and 10, and relative rib pitch between 5 and 60. At Reynolds number 20000, relative rib pitch 17.22, relative rib height 0.044, and relative rib height 0.5, the maximum THP attained is 2.77. CFD simulations and experiments have been used to confirm the ideal design parameter values. The fact that the errors fall within allowable bounds attests to the validity of the empirical correlations that were employed in the design of the solar artificial air heater and the appropriate choice of model equations. Arya *et al*. [19] explained that in a sun powered discuss radiator (SAH) utilizing distinctive shapes of scaled down (V, bend and transverse broken miniature) combined with dimples on safeguard board to make strides warm exchange. For test and recreation think about utilizing ANSYS (Familiar), a dimple with a V-miniature rib was manufactured on a plate (safeguard) as a unpleasantness component. By giving the point of assault (α), relative long way (RLL) length (l/d), relative tallness (harshness) and relative wire lengths (w/Dh) extending from 45 to 75°, 15–25, 0.024–0.036 and 0.14–0.21 individually. The thermohydraulic execution (THP) calculate of the proposed unpleasantness was moreover explored at Reynolds numbers (Re) extending from 5000 to 20000. Comes about of normal Nusselt number, turbulent motor vitality (TKE), liquid stream characteristics and temperature are included to examine the comparative merits of each dimple with smaller than expected courses of action. The comes about uncovered that among dimples with diverse miniatures, 90° transverse broken-miniature with dimple appears best thermohydraulic execution at Re underneath 10,000 whereas a dimple with V-miniature at a point of assault (α) 45° appears the most elevated thermohydraulic execution at Re overn8750. It was found that THP accomplished a most extreme esteem of 1.63 at α = 45°, l/d = 20 and w/Dh = 0.18 at Reynolds number 12,500 for the dimple with a V-miniature rib.

Shaik *et al*. [20] explained how the harshness is presented on the heat-absorbing side within the frame of ribs. A CFD (computational liquid flow) demonstrate has been utilized to recreate the warm enlargement and stream characteristics caused by dimple ribbed through the triangular passaged SAH. The reenactments were conducted through displaying and planning the SAH. For a run of Reynolds number (Re) (4000–17700), the examination considers two harshness parameters, Z/e, Z'/e and X/e by keeping up the tallness of relative harshness of 3 to 7, separately. Compared with ordinary discuss radiators, way better warm exchange enlargement (1-16-8.27%) is watched within the adjusted discuss radiator with ribs. Due to the expansion of manufactured ribs, maximum Nu (38.63 – 96.5%) is watched within the case of Z/e = X/e = 18. Too, the TPP (thermohydraulic execution parameter) encompasses a most extreme esteem of 2.01%.

Conclusion

An attempt has been in the paper to analyse the CFD as well as experimental results concluded by various authors to understand heat transfer coefficients, temperature distribution, velocity profiles and pressure drop across the solar air heater with various types of artificial roughness on the absorber plate. It has been observed that results have been compared with experimental data if available to validate the simulation and adjust parameters if discrepancies are found. Results are further being used to optimize the design of the solar air heater, especially focusing on improving heat transfer efficiency or reducing pressure drop. Many such investigations can further be carried out to explore the insights of the simulation-based analysis.

References

1. Saxena A, El Sebaii AA. A thermodynamic review of solar air heaters. Renewable and Sustainable Energy Reviews,2015:43:863-90.
2. Abbasov Y, Umurzakova M, Sharofov S, Goryayev A. Efficiency of solar air heaters. InE3S Web of Conferences, EDP Sciences,2023:452:04009.
3. Biondi P, Cicala L, Farina G. Performance analysis of solar air heaters of conventional design. Solar Energy,1988:41(1):101-7.
4. Bhargava AK, Garg HP, Agarwal RK. Study of a hybrid solar system—solar air heater combined with solar cells. Energy conversion and Management,1991:31(5):471-9.
5. Layek A, Saini JS, Solanki SC. Second law optimization of a solar air heater having chamfered rib–groove roughness on absorber plate. Renewable Energy,2007:32(12):1967-80.
6. Aharwal KR, Gandhi BK, Saini JS. Heat transfer and friction characteristics of solar air heater ducts having integral inclined discrete ribs on absorber plate. International Journal of Heat and Mass Transfer,2009:52(25-26):5970-7.
7. Bhushan B, Singh R. A review on methodology of artificial roughness used in duct of solar air heaters. Energy,2010:35(1):202-12.
8. Gill RS, Singh S, Singh PP. Low cost solar air heater. Energy Conversion and Management,2012:57:131-42.
9. Kumar V. Experimental investigation on thermal performance enhancement in multi V-Pattern convex protrusion roughened solar air heater. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects,2023:45(4):12118-33.

10. Kumar S, Saini RP. CFD based performance analysis of a solar air heater duct provided with artificial roughness. Renewable energy,2009:34(5):1285-91.
11. Gupta MK, Kaushik SC. Performance evaluation of solar air heater for various artificial roughness geometries based on energy, effective and exergy efficiencies. Renewable Energy,2009:34(3):465-76.
12. Kumar TS, Mittal V, Thakur NS, Kumar A. 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,2011:30:1(3):67-93.
13. Chamoli S, Chauhan R, Thakur NS, Saini JS. A review of the performance of double pass solar air heater. Renewable and Sustainable Energy Reviews,2012:16(1):481-92.
14. Kulkarni K, Kim KY. Comparative study of solar air heater performance with various shapes and configurations of obstacles. Heat and Mass Transfer,2016:52:2795-811.
15. Srivastava RK, Rai AK. A review on solar air heater technology. International Journal of Mechanical Engineering and Technology,2017:8(7):1122-31.
16. Alam T, Kim MH. Heat transfer enhancement in solar air heater duct with conical protrusion roughness ribs. Applied Thermal Engineering,2017:126:458-69.
17. Prakash C, Saini RP. Heat transfer and friction in rectangular solar air heater duct having spherical and inclined rib protrusions as roughness on absorber plate. Experimental Heat Transfer,2019:32(5):469-87.
18. Korpale VS, Deshmukh SP, Mathpati CS, Dalvi VH. Numerical simulations and optimization of solar air heaters. Applied Thermal Engineering,2020:180:115744.
19. Arya N, Goel V, Sunden B. Solar air heater performance enhancement with differently shaped miniature combined with dimple shaped roughness: CFD and experimental analysis. Solar Energy,2023:250:33-50.
20. Shaik R, Punna E, Gugulothu SK. Optimisation of thermohydraulic performance of triangular duct solar air heater with alternative dimple shaped protrusion and intrusion on the absorber plate. Thermal Science and Engineering Progress,2023:42:101957.