A Review on Heat Transfer and Fluid Flow Analysis of Artificially Roughened Solar Air Heater

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ABSTRACT

The Solar technologies has been studied with its classification falls into two groups; passive and active heating. There is a still possibility to enhance system efficiency solar air heater. The Passive solar techniques include designing spaces according to natural circulation, locating buildings with reference to the Sun or selecting high thermal conductive materials. On the other hand, active solar techniques include using solar panels, pumps or fans to convert solar energy into useful outputs. Solar air heaters are devices that utilize solar radiation for a variety of purposes. These devices are simple and can be constructed inexpensively. Mainly, solar air heaters consist of a transparent cover, an absorber plate and insulation material. The air flow enters through the channel that is formed by the absorber plate and the transparent cover. Solar radiation absorbed by the absorber plate. The absorbed heat transferred to the air as it flows along the channel increases its temperature. This heated air can be used in several applications such as drying agricultural products, space heating and air conditioning, water heating and industrial process heating. There are many advantages of solar air heater systems. Firstly, they are simple to maintain and design. After the set-up cost, a solar air heater system has no fuel expenditure. There is less leakage and corrosion when compared to the systems that use liquid. It is also an eco-friendly system which has zero greenhouse gas emissions

Keywords – Heat Transfer, Energy Efficient, Solar Air Heaters.

I. INTRODUCTION

Solar air system is a type of system which collects solar energy and transforms it into heat. The general idea is that the air is flowing through solar collector and heat from sun naturally raises the temperature of the air. In other words cold, outside air is heated and delivered to the room. The collector has on outer layer of glazing/polycarbonate which is exposed to sun. Circulation of the air in the building can be by natural driving forces (buoyancy effect) or by fan which is more certain. Optionally the fan can be powered by solar cell mounted on collector.

Preheating of air supplied to buildings has gained much interest during recent years. The advantage of this technology is that it is cheap and simple. It is especially efficient for summer houses as it can work without anyone's attendance. It can help to get rid of mould and bad smells as well as increase the temperature inside without need of additional heating. In this way the indoor environment in such houses is maintained on a good level after winter

II. LITERATURE SURVEY

Singh et al. [1] numerical investigated has been conducted to analyze the hydro-thermal characteristics of a solar air heaters when its absorber plate has S-shaped pattern dimple roughness. This analysis is conducted for appropriate levels of geometric constraints, such as relative roughness pitch and dimple diameter. The present simulation model has been validated with Dittus–Boelter equation and are found to be in good agreement with it. It was found that S-shaped dimple roughness has yielded 2.45–3.55 times higher Nusselt number value and having 2.81–4.54 times larger friction factor compared to smooth solar air heater. It was observed that as dimple diameter increases, the Nusselt number increases but upto 2.8 mm and afterwards it decreases. Similar trend is also observed for relative pitch roughness, where it increases upto 10 and starts declining afterwards. Furthermore, the optimum solar air heater configuration has also been identified in terms of Nusselt number and friction factor. Among all configurations, maximum thermo hydraulic performance value of 2.15 was obtained for dimple diameter of 2.8 mm and relative pitch roughness of 10 at Reynold number of 20,000.

Kant et al. [2] experimentally studied the effect of rib roughness on absorber. In this paper, an effort has been made to improve the heat transfer efficiency of SAH by utilizing hybrid ribs. Hybrid rib roughnesses are designed to integrate V-shaped ribs downstream of arc-shaped ribs and were experimentally tested in the SAH duct at Reynolds numbers (RN) between 2000 and 16,000. The various roughness pattern i.e. arc angle (α), relative V ribs position (d/w), relative rib pitch (p/e) and relative rib height (e/Dh) have been exploited in the range of 30º-75º, 0.2–0.8, 8–14 and 0.036–0.056, respectively. As a result, maximum enhancement in NuNu has been found as 3.75 at $\alpha = 45º$, d/w = 0.5, p/e = 12, e/D = 0.056. Thermohydraulic Performance (TP) parameters have also been evaluated for all set of parameters and it was found to be maximum 2.49 at $\alpha = 45º$, d/w = 0.5, p/e = 12, and e/Dh = 0.036.

Abbasov et al. [3] 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 sheet along the main direction of the airflow.

Kumar [4] explained how the active viscous laminar sub-layer on the surface of the absorber limits the heat transmission coefficient of solar air heaters (SAHs). 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, $\alpha = 60º$, 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.

Arya et al. [5] 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 $\alpha = 45°$, l/d = 20 and w/Dh = 0.18 at Reynolds number 12,500 for the dimple with a V-miniature rib.

Shaik et al. [6] 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%.

Ankur Haldar et al. [7] had performed a computational fluid dynamics analysis of a solar air heater with artificial wavy roughness. Roughness elements were studied for twelve wavy surface configurations with rib heights (*e*) of 0.7 mm, 1 mm, and 1.4 mm and pitch (*p*) of 10, 15, 20, and 25 mm. A 2D computational domain is modelled and the involved differential equations are solved using a finite volume method. To solve the transport equations for turbulent flow and energy dissipation rate, the RNG k-ε turbulence model with enhanced wall function is employed. For a uniform heat flow of 1000 W/m^2, the effect of roughness parameter on Nusselt number, friction factor, and thermo-hydraulic performance parameter (THPP) is investigated. On the basis of the THPP, the best geometric parameter values are found in the Reynolds Number (*Re)* range of 3800–18,000. At Re of 12,000, the optimal THPP is 1.96, which corresponds to a rib height of 0.7 mm and a pitch of 15 mm.

Harvindra singh et al. [8] studied the structure of the kite shaped roughness applied to solar air heater which was designed with the help of *CFD*. The presented model is designed in *CFD* ANSYS software because it is very easy to flow fluid without any problem of intake air or fluid. The Kite shaped roughness is used to acquire all the details of the fluid in the form of the heat transfer rate and these results are carried out with *RNG k-ε* model for range of Reynolds number from 1500 to 4000. The rate of thermal characteristics enhanced with increasing pitch space between the different height of Kite shaped roughness (e_k = 1.2, 2.2, 3.2 and 4.2 mm) ratio p/e_k = 25 – 112.5 and observed maximum THP for Reynolds number *Re* = 4000, pitch space *p* = 125 mm, and height of Kite shaped roughness e_k = 2.2 mm.

Raminder singh gill et al. [9] had experimental and computational investigation of solar air heater using hybrid configuration of broken arc and staggered rib for heat transfer enhancement. The performance of the solar air heater is investigated through a series of experimental trials by varying flow and geometrical parameters like non-dimensional staggered rib position (0.2–0.8), roughness pitch (4–12), gap width (0.5–2.5), gap position (0.2–0.8), roughness height (0.022–0.043), arc angle (15°-75°), staggered rib piece size (1–6), and Reynolds number(2000–16000). The impact of staggered rib on the fluid flow pattern has been observed using numerical approach based on Finite volume method. The proposed design increases the friction factor & Nusselt number by 2.57 and 3.16 times respectively in comparison with a smooth duct. Moreover, the Nusselt number augments by 1.22 times in comparison with broken arc rib. The optimum values of both the flow and geometric parameters are evaluated and empirical correlations for pressure loss & Nusselt number are also reported. It is concluded that the thermal–hydraulic performance of the proposed hybrid rib roughness (2.33) is found to be superior in comparison with similar rib roughness geometries.

Anil singh yadav et al. [10] had investigated CFD-based correlations for ribbed roughened solar air heater. An absorber plate of *SAH* (solar air heater) attached with circular ribs is analyzed in this article. ANSYS Fluent v16 is utilized to analyze the turbulent airflow for different arrangements of rib. All results are based on CFD (computational fluid dynamics) simulations. The analysis is carried out within the limits of *Re* from 3800 to 18,000 and *P* from 10 to 25. The resulting data is reduced into correlations using a linear stepwise regression algorithm. The developed equations for artificially roughened heater of solar air predict all the data for friction factor and Nusselt number within ±5% relative absolute deviation.

Leila N. Azadani et al. [11] had investigated the effect of discrete cylindrical shape roughness elements on the heat transfer and flow characteristics of a square duct solar air heater using Computational Fluid Dynamics (CFD) simulations. A multi objective optimization algorithm was applied to find the optimum values of four roughness parameters including the roughness diameter (*d*), height (*e*), longitudinal pitch (*L*), and transverse pitch (*S*). The objectives of the optimization were maximizing the Nusselt number (*Nu*) and minimizing the friction factor (*f*). The optimization procedure includes designing of experiments, generating response surfaces, and determining optimum roughness parameters. The optimal space filling design (OSFD) of experiment method was employed to investigate the effect of roughness parameters on the Nusselt number and friction factor with a minimum number of numerical experiments. Once the designed numerical experiments were performed, the Kriging response surface method was used to express the relationships between the Nusselt number and friction factor with the roughness parameters. Then, the non-dominated sorting genetic algorithm II (NSGA II) was applied to determine the optimum roughness parameters. The optimum values of roughness diameter, height, longitudinal pitch, and transverse pitch relative to the channel height (*H*) were found to be $d/H = 0.055$, $e/H = 0.053$, $L/H = 0.192$, and $S/H = 0.158$, respectively which yielded a thermo hydraulic performance parameter of 1.20.

Korpale et al. [12] 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 considering 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.

Rohit Misra et al. [13] studied the duct of equilateral triangular cross section having V-down ribs with multiple gaps and turbulence promoters as artificial roughness is analyzed and thermo-hydraulic response of duct is measured. For in depth analysis computational fluid dynamics analysis has been carried out using ANSYS FLUENT 19.0. Under the parametric variation part, effect of change in roughness parameters, viz., relative roughness pitch and angle of attack on thermohydraulic performance has been explored. Flow Reynolds number (Re) is systematically varied from 4,000 to 20,000. Proposed roughness proves its worth as its attachment over the absorber leads to an enhancement in Nusselt number and friction factor both, because of enhanced level of interaction among the fluid particles. Study reveals that upon varying the relative roughness pitch (P/e) from 8 to 14 and angle of attack from 45º to 60º, maximum heat transfer rate is attained at P/e = 10 and α = 45º, respectively, irrespective of Reynolds number.

Ankur Srivastava et al. [14] had numerically studied the dissimilar types of repeated-rib roughness: arc-shape with gap and V-shape with gap on the absorber plate of the solar air heater having similar shape and size working under identical boundary conditions. Relative gap width (g/e) of 1, relative roughness height of 0.04, the relative roughness pitch of 10, p/P = 0.65, d/W = 0.69, No. of gaps = 1, attack angle $\alpha = 60^0$ of the rib, heat flux 1000 W/m^2, etc. are kept constant and variation in range of Reynolds number is 3000–15000. Numerical simulations are conducted with the help of ANSYS CFD tool, and results have been validated with the experimental studies. The V-shape ribs have maximum frictional loss penalty of 4.05 and Nusselt number enhancement of 3.4 at Re 3000. The arc-shape ribs have maximum frictional loss penalty of 3.94 and Nusselt number enhancement of 2.4 for Re 15000. The maximum THPP for the V-shape ribs and arc shape ribs are 2.21 and 1.5 respectively at Re 3000.

Parkash and Saini [15] 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.

Srivastav et al. [16] 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 [17] 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 ($0.020 \leq e/D \leq 0.044$) and relative rib pitch ($6 \leq p/e \leq 12$) on Nusselt number and friction factor have been investigated. 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.

Kulkarni and Kim [18] conclude that the best shape for obstructions as shown in the Fig. 9 attached to a solar air heater was investigated using three-dimensional Reynoldsaveraged Navier-Stokes analyses of fluid flow and 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.

Saxena et al. [19] 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. 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.

Biondi et al. [20] 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, 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. [21] 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.

Layek et al. [22] 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.

III. Conclusion

This paper reviews the literature related to efficiency of solar air heater system. The main conclusion from the paper is given below:

1. Roughness geometries like S-shaped dimples, V-shaped ribs, arc-shaped ribs, kite-shaped, and cylindrical roughness were investigated using CFD and experiments to improve heat transfer and thermohydraulic performance of solar air heaters.

2. Studies showed significant enhancement in Nusselt number (up to 3.75 times) and friction factor with artificial roughness. The best thermohydraulic performance (up to 3.29) was achieved for specific configurations, balancing heat transfer and pressure drop.
3. Computational optimization techniques, including response surface methods and multi-objective algorithms, were employed to find ideal roughness parameters for maximum heat transfer efficiency.
4. Experimental data validated the CFD simulations, confirming the reliability of artificial roughness designs and correlations for Nusselt number and friction factor.

References:

1. Singh, J., Bisht, V.S., Bhandari, P. *et al.* Computational parametric investigation of solar air heater with dimple roughness in S-shaped pattern. *Int J Interact Des Manuf* **18**, 2969–2979 (2024).
2. Kant, R., Alam, T., Singh, D., & Sabeeh, A. (2024). Performance improvement of solar air heater duct-employing rib roughness on absorber: an experimental study. *Experimental Heat Transfer*, *37*(7), 1139–1154.
3. Abbasov Y, Umurzakova M, Sharofov S, Goryayev A. Efficiency of solar air heaters. InE3S Web of Conferences, EDP Sciences,2023:452:04009.
4. 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.
5. 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.
6. 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.
7. Ankur Haldar, L. Varshney, Prashant Verma, Effect of roughness parameters on performance of solar air heater having artificial wavy roughness using CFD, Renewable Energy, Volume 184, 2022, Pages 266-279.
8. Harvindra Singh, Himmat Singh, Rahul Bahuguna, Chandra Kishore, CFD analysis of heat transfer characteristics of rectangular solar air heater with kite shaped roughness, Materials Today: Proceedings, Volume 52, 2022, Pages 2014-2025.
9. Raminder Singh Gill, Vishavjeet Singh Hans, Rupinder Pal Singh, Optimization of artificial roughness parameters in a solar air heater duct roughened with hybrid ribs, Applied Thermal Engineering, Volume 191, 2021, 116871.
10. Anil Singh Yadav, Vipin Shrivastava, Abhishek Sharma, Mayank Kumar Dwivedi, Numerical simulation and CFD-based correlations for artificially roughened solar air heater, Materials Today: Proceedings, Volume 47, Part 11, 2021, Pages 2685-2693.
11. Leila N. Azadani, Nadiya Gharouni, Multi objective optimization of cylindrical shape roughness parameters in a solar air heater, Renewable Energy, Volume 179, 2021, Pages 1156-1168
12. Korpale VS, Deshmukh SP, Mathpati CS, Dalvi VH. Numerical simulations and optimization of solar air heaters. Applied Thermal Engineering,2020:180:115744.
13. Rohit Misra, Jagbir Singh, Sheetal Kumar Jain, Sachin Faujdar, Muskan Agrawal, Arin Mishra, Pradeep Kumar Goyal, Prediction of behavior of triangular solar air heater duct using V-down rib with multiple gaps and turbulence promoters as artificial roughness: A CFD analysis, International Journal of Heat and Mass Transfer, Volume 162, 2020, 120376.
14. Ankur Srivastava, Gaurav Kumar Chhaparwal, R.K. Sharma, Numerical and experimental investigation of different rib roughness in a solar air heater, Thermal Science and Engineering Progress, Volume 19, 2020, 100576.
15. 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.
16. Srivastava RK, Rai AK. A review on solar air heater technology. International Journal of Mechanical Engineering and Technology,2017:8(7):1122-31.
17. Alam T, Kim MH. Heat transfer enhancement in solar air heater duct with conical protrusion roughness ribs. Applied Thermal Engineering,2017:126:458-69.
18. 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.

19. Saxena A, El Sebaii AA. A thermodynamic review of solar air heaters. Renewable and Sustainable Energy Reviews,2015:43:863-90.
20. Biondi P, Cicala L, Farina G. Performance analysis of solar air heaters of conventional design. Solar Energy,1988:41(1):101-7.
21. 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.
22. 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.