Review on Optimization of Thermal-Hydraulic Efficiency of Solar Air Heater with Roughened Absorber Plate by CFD

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Abstract: *The thermal performance of solar air heater is generally poor due to low heat transfer coefficient between the absorber plate and air flowing in the duct. In order to improve the thermal performance artificial roughness is provided on the underside of absorber plate due to which turbulence is created in the heat transfer zone and ultimately performance of solar air heater improves considerably and analyses by CFD.*

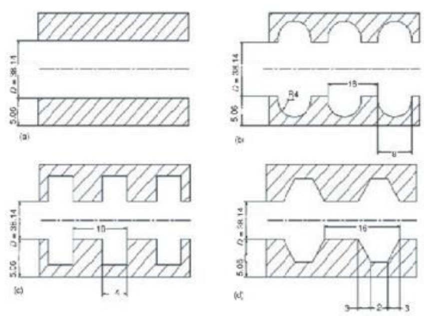
Key Words: *Solar Air Heater, CFD Analysis, Artificial Roughness, Roughness Geometry ,thermo-hydraulic performance, Reynolds number, Nusselt number, Friction Factor.*

1. INTRODUCTION:

Solar air heater is one of the basic types of solar collectors which absorbs the incoming solar radiations and converted it into thermal energy for various thermal applications. It has been found that the conversion of solar radiation to thermal energy is poor in the conventional solar air heater due to the low heat transfer coefficient between the absorber plate and working fluid of the solar air heater. The use of artificial roughness on the absorber plate is one of the effective techniques to enhance the rate of heat transfer to flowing fluid in a solar air heater. It has been observed that the artificial roughness applied on the absorber plate breaks the laminar sub layer, which reduces thermal resistance and increase heat transfer coefficient. Solar air heater are the cheapest and extensively used solar energy collection devices employed to deliver heated air at low to moderate temperatures for various applications. These types of solar air collectors collect solar energy and covert this energy in form of hot air. Conventional type of solar air collector have lower thermal efficiency than concentrating type of solar air collectors, but because of low operating cost and maintenance cost, they are widely used as a heating media. Useful heat energy from flat plate solar air heaters can be used in many thermal applications in drying agricultural products such as in seeds, fruits, and vegetables and residential also some time in industries and as a auxiliary heater for heating building in winter time.

2. LITERATURE REVIEW:

Ponnusamy SELVARAJ et.al.[2013] [1] had done CFD analysis on heat transfer and friction factor characteristics of a turbulent flow for internally grooved tubes (circular,square,trapezoidal) Water was used as the working fluid. Tests were performed for Reynolds number ranges from 5000 to 13500 for plain tube and different geometry inside grooved tubes. The maximum increase of pressure drop was obtained from numerical modeling 74% for circular, 38% for square, and 78% for trapezoidal grooved tubes were compared with plain tube. Based on computational fluid dynamics analysis the average Nusselt number was increased up to 37%, 26%, and 42% for circular, square and trapezoidal grooved tubes, respectively, while compared with **Fig.1. The geometric shapes of the grooved tubes in mm; (a) plain tube,** the plain tube. The thermal hydraulic performance was obtained **(b) circular grooved tube, (c) square grooved tube, and (d) trapezoidal grooved tube.** From computational fluid dynamics analysis up to 38% for circular grooved tube, 27% for square grooved tube and 40% for trapezoidal grooved tube while compared with the plain tube.



Suman Saurav & V.N.Bartaria[2013] [2] had done cfd analysis of heat transfer in a rectangular duct of a solar air heater having triangular rib roughness on the absorber plate The effect of Reynolds number on Nusselt number was investigated to study the heat transfer, friction factor and flow characteristics in a solar air heater having triangular rib roughness on the absorber plate. The computations based on the finite volume method with the SIMPLE algorithm have been conducted for the air flow in terms of Reynolds numbers ranging from 4000 – 20000 and p/e (4 to 20).

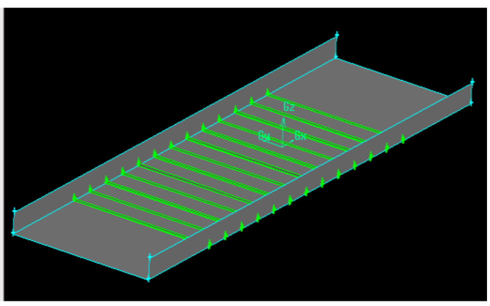


Fig. 2 Schematic of two-dimensional solution domain for CFD analysis.

Anil Singh Yadav & J.L. Bhagoria [2014][3] had done cfd based thermo-hydraulic performance analysis of an artificially roughened solar air heater having equilateral triangular sectioned rib roughness on the absorber plate. Twelve different configurations of equilateral triangular sectioned rib (P/e = 7.14–35.71 and e/d = 0.021–0.042) have been used as roughness element. It has been observed that for a given constant value of heat flux (1000 W/m2), the performance of the artificially roughened solar air heater is strong function of the Reynolds number, relative roughness pitch and relative roughness height. Optimum configuration Of the roughness element for artificially roughened solar air heater is evaluated.

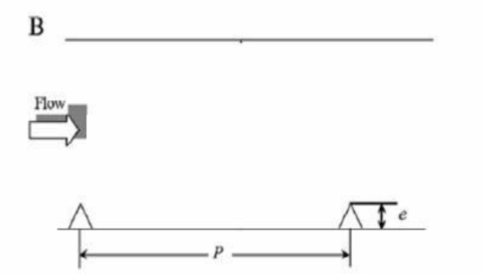


Fig. 3 Geometric shape of equilateral triangular rib.

A.Boulemtafes-Boukadoum & A.Benzaoui [2014][4] had done cfd based analysis of heat transfer enhancement in solar air heater provided with transverse rectangular ribs. They solved continuity, momentum and energy equations in turbulent model using four closure models k-ε RNG, k-ε RZ, k-ω standard, k-ω SST. The effect of major parameters (Reynolds Number, Nusselt Number, Friction Factor global thermo hydraulic performance parameter.etc.) was examined and discussed. The results obtained are concordant to those found in the literature and shows clearly the heat transfer enhancement without big penalty of friction loss.

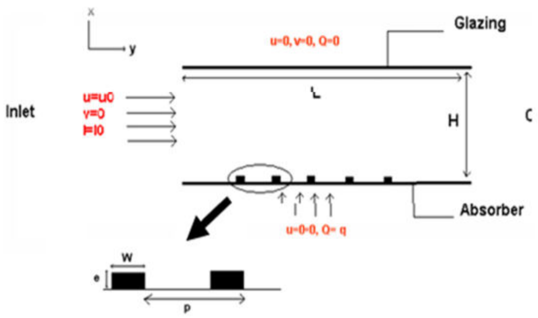


Fig. 4 Geometric configuration

ANIL KUMAR [2014][5] had done cfd analysis of heat transfer and fluid flow in different shaped roughness elements on the absorber plate solar air heater. The effect of geometries on heat transfer and friction factor and performance enhancement was investigated covering the range of roughness parameters V shaped, Multi v-shaped ribs, Multi v-shaped ribs with gap and working parameters. Different turbulent models have been used for the analysis heat transfer and friction factor and their results are . compared with Dittus-Boelter Empirical relationship for smooth surface. Renormalization k-epsilon model based results have been found in good agreement and accordingly this model is used to predict heat transfer and friction factor in the duct.

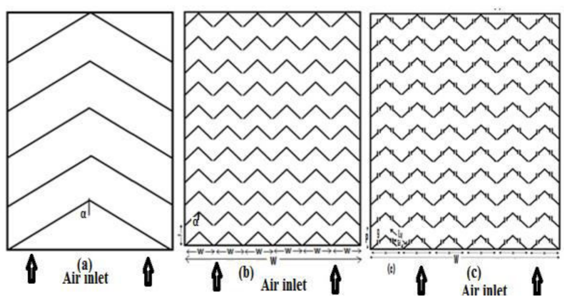


Fig 5. (a) V-shaped (b) Multi v-shaped (c) Multi v-shaped with gap

Manish Kumar and Varun [2014][6] had done cfd investigation of solar air heater duct provided with inclined circular rib as artificial roughness. The roughness parameters were studied in the present work are inclination angle (α) of ribs 45º and 60º and roughness height (e) 1mm and 2mm at a constant roughness pitch (p) of 20mm. Reynolds number (Re) in the range of 6000 to 15000 and constant heat flux (I) having a value of 1000W/m 2 on absorber plate were used as operating parameter during the analysis. Renormalization group (RNG) k- ε turbulence model is selected for the analysis from the different turbulence model after comparing the results of these models with empirical correlation results for smooth duct, as RNG k- ε model results as found in good agreement. The effect of different roughness parameters has also been compared on the basis of overall enhancement ratio to obtain the optimum roughness parameters.

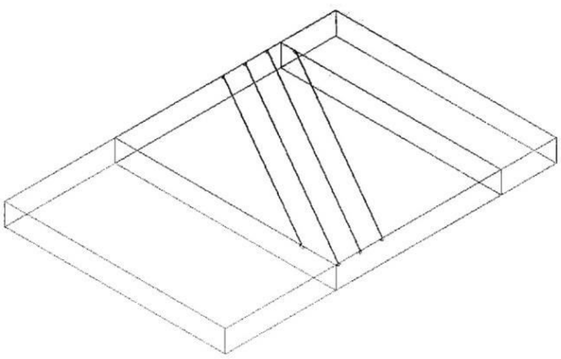


Fig. 6: Solution Domain

Ashok Singh Yadav et.al. [2015][7] had done CFD based analysis of solar air heater having v-shaped perforated blocks on absorber plate. The commercial finite-volume based CFD code ANSYS FLUENT 14 is used to simulate turbulent airflow through artificially roughened solar air heater. The RNG k–ε turbulence model is used to solve the transport equations for turbulent flow energy and dissipation rate. The investigation encompassed the geometrical parameter namely, relative blockage height (e/H) of 0.4–1.0, relative pitch ratio (P/e) of 4–12 and open area ratio (β) of 5–25% at a fixed angle of attack (α) of 60° . The maximum enhancement in Nusselt and friction factor has been found to be 6.38 and 13.96 times to that of smooth duct, respectively.

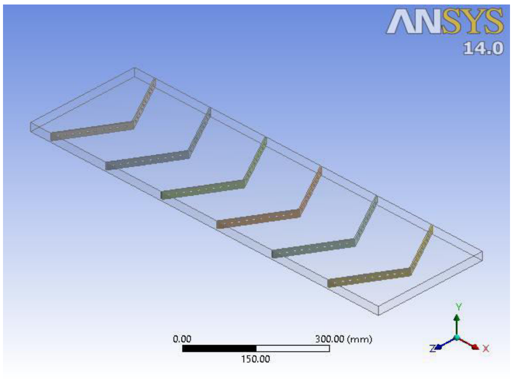


Fig -7: Geometry of the Model

Kishor Kulkarni et.al.[2015][8] had founded that the constructed surrogate models show good prediction accuracies for the objective functions compared to the RANS results at the representative PODs; maximum relative errors of 1.5% for F Nu and 11.723% for Ff with the RSA model, and 4.824% for F Nu and 11.342% for Ff with the Kriging model. The analyses of flow and temperature fields indicate that the larger values of e/H And θ cause larger flow recirculation zones behind the obstacles, resulting in a larger interruption in the flow path and thus the larger pressure loss. Also, the larger flow recirculation produces a higher production rate of turbulent kinetic energy, and thus an enhanced heat transfer rate. The performance factor was used to select optimum PODs with respect to the overall thermal hydraulic performance. POD 8, which represents the design with the lowest friction loss, shows the highest performance factor among all PODs. Designers are expected to select an optimum design among the Pareto-optimal designs reflecting their design requirements. The proposed numerical optimization technique provides an efficient way to reduce the computational and experimental costs when designing SAHs.

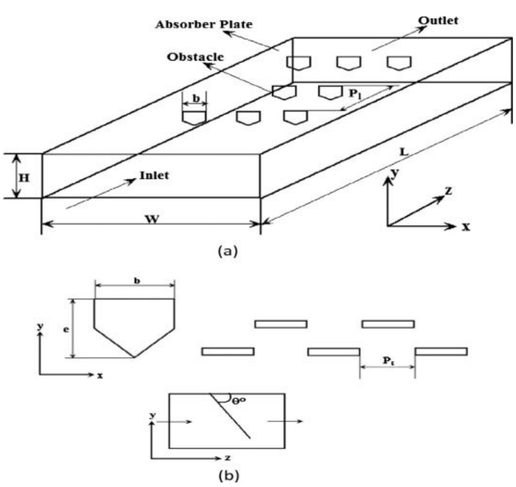


Fig.8. SAH model.(a) Schematic of SAH and(b)design variables

Vivek Rao et.al.[2015][9] had done CFD based heat transfer analysis of solar air heater duct provided with artificial roughness. The aspect ratio of the duct was kept constant as 5. Symmetry and periodic boundary conditions are used to minimize the computational cost. Four rib configurations were tested: V-up rib, V-up Broken rib, V-down broken rib, and Multi V rib pointing upstream of the main flow direction. Profile boundary condition was created at the outlet of the test section and was applied to various inlet conditions of main rib configuration. For all cases hydraulic diameter and angle of attack were kept constant to 33 mm and 600. Only relative roughness pitch and Reynolds number were varied from 8-12 and 8000-15000. Solar air heater provided with Multi-V rib gives maximum Nusselt number of 145 at relative roughness pitch of 8 and Reynolds number of 15000.

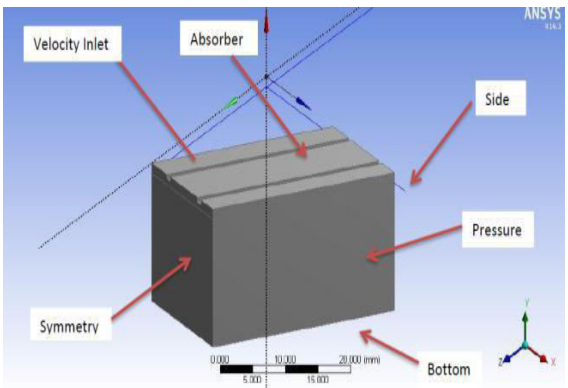


Fig.9. Geometric model

Amit Kumar Ahuja & J.L.Bhagoria [2015][10] had done A CFD based Thermo-Hydraulic Performance Analysis of an Artificially Roughened Solar Air Heater Having Circular Ribs on the Absorber Plate. The input parameter for the analysis is taken as Reynolds no (Re), relative roughness height (e/D) and relative roughness pitch (P/e).A three-dimensional simulation is conducted using k-e turbulence model in ANSYS FLUENT 14.5 code. Due to artificial roughness heat transfer increases as compared to smooth duct. The present investigation shows the effect of input design parameter on various thermal properties like nusselt number and average friction factor. For the range investigated and for this type of rib arrangement maximum value of thermo-hydraulic performance parameter is found to be 1.631.

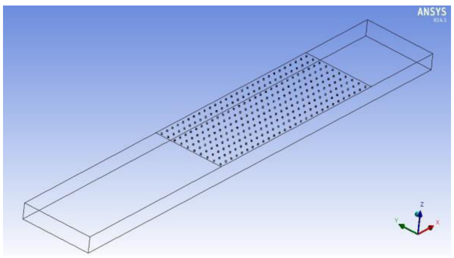


Fig.10. 3-Dimensional domain SAH duct with circular ribs on absorber

Amin Ebrahimi & Benyamin Naranjani[2016][11] had done An investigation on thermo-hydraulic performance of a flat-plate channel with pyramidal protrusions. It is observed that utilizing these configurations can boost the heat transfer up to 277.9% and amplify the pressure loss up to 179.4% with a respect to the plain channel. It is found that the overall efficiency of the channels with pyramidal protrusions is improved by 12.0–169.4% compared to the plain channel for the conditions studied here. Furthermore, the thermodynamic performance of the channel is investigated in terms of entropy generation and it is found that equipping the channels with pyramidal protrusions leads to lower irreversibility in the system.

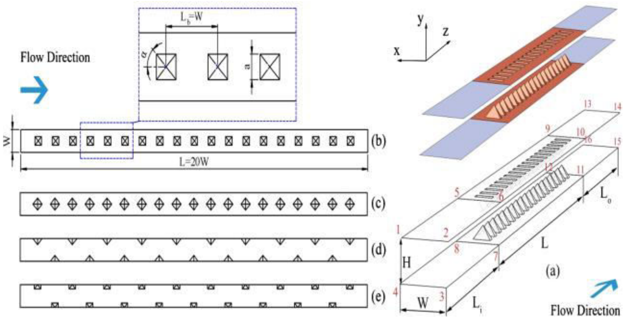


Fig.11. Physical model and relevant geometrical parameters of the channel with pyramidal protrusions.

Rajeev Ranjan.et.al.[2016][12] had done CFD analysis of thermal performance in Isosceles Right Triangle Rib Roughness on the absorber plate solar air heater. In all cases the average Nusselt number tends to increase as Reynolds number increases. The average friction factor has been found to be 3.45 times over the smooth duct. It has been observed that the average friction factor tends to decrease as the Reynolds number increase. Increment in thermal performance obtained for maximum thermo-hydraulic performance is obtained for relative roughness pitch of 5 and relative roughness height 0.045.

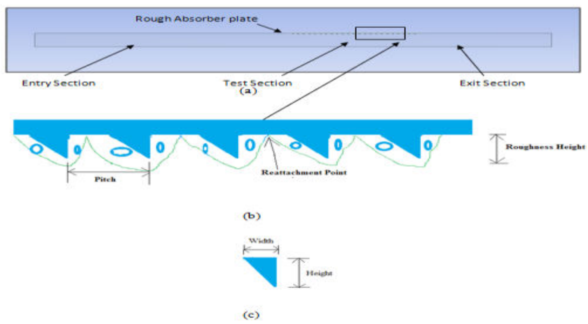


Fig.12. (a) Roughened plate(b) Magnified view (c) Rib shape.

Anil Kumar and Man-Hoe Kim [2016][13] had done CFD analysis of thermal hydraulic performance in a solar air heater channel with multi v-type perforated baffles. THE flow passage has an aspect ratio of 10. The relative baffle height, relative pitch, relative baffle hole position, flow attack angle, and baffle open area ratio are 0.6, 8.0, 0.42, 60, and 12%, respectively. The Reynolds numbers considered in the study was in the range of 3000–10,000. The re-normalization group (RNG) k-"turbulence model has been used for numerical analysis, and the optimum relative baffle width has been investigated considering relative baffle widths of 1.0–7.0.The numerical results are in good agreement with the experimental data for the range considered in the study. Multi V-type perforated baffles are shown to have better thermal performance as compared to other baffle shapes in a rectangular passage. The overall thermal hydraulic performance shows the maximum value at the relative baffle width of 5.0.

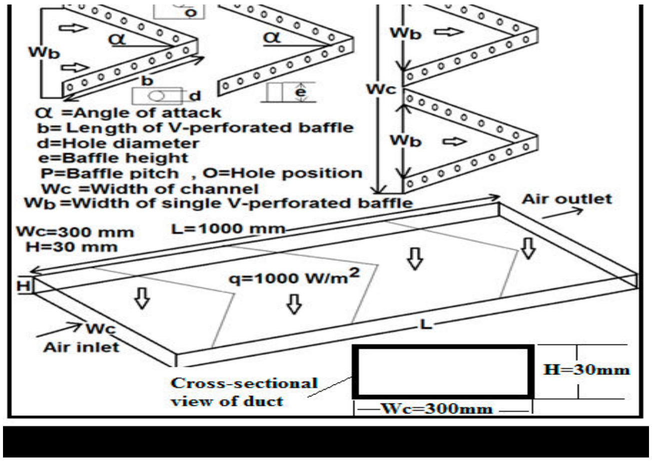


Fig.13. Multi V-shaped perforated baffle shape.

3. LITERATURE SURVEY:

The above survey infers that lot of CFD analysis work had been done by various researcher and parameters like heat transfer rate, friction factor, pressure drop, entropy generation, solar radiation, Reynolds number, Nusselt number , relative roughness height (e/D) , relative roughness pitch (P/e),effect of pitch and effect of different surface roughness's on thermal hydraulic performance of solar air heater have been studied. There is a different shapes of ribs like circular, square, trapezoidal, pyramidal, rectangular, v-shape, multi v-shape, multi V-shape with gap geometries, circular inclined rib ,isosceles right triangle shape, equilateral triangular sectioned rib ,triangular transverse wire rib ,v-up rib ,v-up broken rib ,v-down broken rib, v-shape perforated blocks-shape rib, diamond shaped rib, arc roughness with gap etc. have been analyzed.

4. COMPARISON OF CFD WORK ON VARIOUS ROGHENED SURFACES :

SR NO.	YEAR	INVESTIGATOR	GEOMETRICAL SHAPES	PARAMETER	RESULTS FOUND
1	2013	Ponnusamy SELVARAJ, Jagannathan SARANGAN, and Sivan SURESH [1]	INTERNALLY GROVED TUBES PLAIN,CIRUCLAR,SQUARE,TRAPEZOIDAL	1) A plain carbon steel tube:- D_i = 38.14 mm D_O = 48.26 mm. 2) Types of Grooves • Circular :- depth=4mm length= 8mm • Trapezoidal: depth=4mm length= 8mm. • Square :- depth=4mm length=4mm 3) P= 16 mm. 4) Re = 5000-13500.	1) h for • Trapezoidal =1503-1843 W/m^2K • Square = 1299-1265 W/m^2K • Circular = 1439-1784 W/m^2K 2) η for • Circular = 26% • Square = 24% • Trapezoidal = 30% higher as compared with plain tube. 3) Nu. increases with the increase of Re.
2	2013	Suman Saurav and V.N.Bartaria [2]	TRIANGULAR TRANSVERSE WIRE RIB	1)A 2-D CFD analysis 2) Re = 4000 - 20000 3) p = 8,16,24,32, 40 4) p/e = 4,8,12,16,20	1. Nu.= increases with the increase of Re. 2. Nu = 1.3 to 1.4 times as compared to smooth duct. 3. Nu is maximum for p= 4 mm. 4. f = decreases with an increase of Re. 5. maximum value of f= 1.1066 when p= 4 and Re= 4000.
3	2014	Anil Singh Yadav & J.L. Bhagoria [3]	EQUILATERAL TRIANGULAR SECTIONED RIB	1) Re = 3800 - 18,000. 2) P/e = 7.14–35.71 3) e/d = 0.021–0.042	1. The performance of the artificially roughened solar air heater is strong function of the Re., relative roughness pitch and relative roughness height for heat flux 1000 W/m^2k
4	2014	A.Boulemtafes-Boukadoum & A.Benzaoui [4]	TRANSVERSE RECTANGULAR RIBS	1) H=40 MM, 2) e=3.4 mm, 3) W=5.8 mm, 4) P= 34mm 2) Re = 3000 - 15000.	1. St. increases with the Re. 2. Stanton number is 1.3 to 1.8 times, higher than smooth duct, for Re = 10000. 3. f decreases with the increase in the Re. 4. A good parameter of performance (ET> 1) is recorded in all the range of Reynolds numbers. 5. ET increases appreciably with the increase in the Re.
5	2014	Anil Kumar [5]	DIFFERENT SHAPED thin circular wire in V-shaped, Multi v-shaped ribs and Multi v-shaped ribs with gap geometries	1) V-shaped rib: P/e=10, e/D=0.043, α=60° 2) Multi v-shaped rib: W/w=6, P/e=10, e/D=0.043, α=60° 3) Multi v-shaped ribs with gap: W/w=6,	1. CFD values and experimental values of heat transfer (Nusselt number) very close to each other. 2. The maximum value of h and f observed with the Multi v-shaped ribs with gap. 3. h is increased to 1.7,4.7,5.6 times for V-shaped, Multi v-shaped and Multi v-shaped with gap ribs roughened respectively as compared to smooth surface.

				P/e=10, e/D=0.043, α=60°, g/e=1.0, Gd/Lv=0.69.	
6	2014	Manish Kumar and Varun [6]	CIRCULAR INCLINED RIB	1. α = 45º and 60º 2. e = 1mm and 2mm 3. p = 20mm. 4. Re = 6000 - 15000 5. I = 1000W/m2 6. Duct :- H = 20 mm W = 200 mm. L = 300 mm.	1. For the value of Re 6000 to almost 8000, the value of overall enhancement ratio is greater than 1. 2. For all different type of roughness geometry, the value of overall enhancement ratio is highest at Re=6000 and after that it decreases sharply up to Re=9000 and further there is a slight increase after that very less decrement in overall enhancement ratio from Re= 12000 to 15000. 3. Solar air heater gives the best performance with roughness geometry having relative inclination angle 0.666 and relative roughness height 0.0275.
7	2015	Ashok Singh Yadav1, Tarun Singh Samant2, Lokesh Varshney3 [7]	V-SHAPE PERFORATED BLOCKS	1. Re= 2000 - 20,000 2. Duct :- W = 100mm H = 20mm , L = 640mm, 3. e/H = 0.4–1.0, 4. P/e = 4–12 5. (β) = 5–25% 6. α = 600.	1) Nu. up to 6.38 times while f rises up to 13.96 times. 2) Maximum Nu.occurs at β of 20%, relative e/H of 0.8, and P/e of 8, 3) maximum f is found corresponding to β of 5%, relative e/Hof 1.0, and relative P/e of 4.
8	2015	Kishor Kulkarni, Arshad Afzal, Kwang-Yong Kim [8]	PENTAGON	1)Re = 6800 2) Pl=e ¼ 2:33 3) e=H = 0.25–0.75 4) Pt=b = 1.66–3 5) h = 30–90	1) The constructed surrogate models show good prediction accuracies for the objective functions compared to the RANS results at the representative PODs; maximum relative errors of 1.5% for F, Nu and 11.723% for Ff with the RSA model, and 4.824% for F, Nu and 11.342% for Ff with the Kriging model.
9	2015	Vivek Rao, Dr. Ajay Gupta, Amit Kumar [9]	V-up rib, V-up Broken rib, V-down broken rib, and Multi V rib	1) Re = 8000, 12000, & 15000. 2) p/e = 8,10, & 12. 3) e/D= 1 4) α = 600.	1) In the medium range of Re, Multi V ribs resulted in higher Nusselt number of 143.885 at relative e/D = 0.03, relative p = 8 2) Re= 15000 with medium range of pressure drop 2.2825 Pa. 3) Secondary flow and vortices' substantially increases the heat transfer rate, which is more effective in V-down broken rib after Multi V rib.

10	2015	Amit Kumar Ahuja & J. L. Bhagoria [10]	CIRCULAR RIB	1. DUCT:- L = 640mm, H=20mm and W=100mm. 2. e = 1 mm to 1.4 mm 3. I = 1000 w/m2 4. Re = 8000-180000 5. Pr 0.7441 6. P/e = 7.14-20 7. e/D = 0.03-0.042 8. Hydraulic diameter 33.33 9. p/e = 10,15 and 20 10. e/d = 0.03 and 0.042	1) Maximum Nu. has been found to be 2.223 times compared to smooth duct corresponds to relative e/D= 0.042 and P/e = 7.142 at Re=15000 . 2) η varies between 1.083 and 1.631. 4) Optimum value of η = 1.631, has been found corresponds to relative e/D = 0.042 and P/e = 10.714 for the Re=15000.
11	2016	Amin Ebrahimi , Benyamin Naranjani [11]	Pyramidal	1) Re= 135 to 1430. 2) H = 3W/4. 3) Li = Lo= L/2 where L = 20W [17–19]. 4) Nineteen equally spaced pyramidal protrusions (Lb =W) are located in the main zone with inline and staggered arrangements.	1) The surface patterns with pyramids mounted at α = 45 generate stronger vortices and show the best overall efficiencies. 2) The larger the protrusion height and width, the higher the overall performance. 3) These configurations can boost the heat transfer up to 277.9% and amplify the pressure loss up to 179.4% with a respect to the plain channel. 4) Overall efficiency is improved by 12.0–169.4% compared to the plain channel .
12	2016	Rajeev Ranjan,M. K. Paswan and N. Prasad [12]	ISOSCELES RIGHT TRIANGLE SHAPE	1) Reynolds = 3593 - 15000, duct aspect ratio=5:1, 2) P/e= 3.33-40(12 values) 3) e/D = 0.015-0.045(3 values) 4) DUCT:- H = 20 MM L = 465 MM.	1) Nu. increase as Re. increases. 2) f = 3.45 times over the smooth duct. 3) f decrease as the Re increases. 4) Maximum η is obtained for p = 5 and e/D= 0.045.
13	2016	Anil Kumar and Man-Hoe Kim [13]	MULTI V - TYPE PERFORATED BAFFELS	1) Wc/Wb = 1.0–7.0 2) e/H = 0.6 3) P/e = 8.0 4) O/e = 0.42 5) Open area ratio12% 6) α = 60 7) Re = 3000–10,000 8) q = 1000 W/m2 9) Pr = 0.71 10) Wc/H = 10	1) η is maximum at Wc/Wb = 5.0, e/H = 0.6, P/e = 8.0, O/e = 0.42, = 12%, and α = 60 .

5. CONCLUSION:

1. Nusselt number increases with the increase of Reynolds number.
2. The average nusselt number decreases with increases in relative roughness pitch in all cases for fixed value of relative roughness height.
3. The average nusselt number increase with increases in relative roughness height in all cases for fixed value of relative roughness pitch.
4. Friction factor decreases with an increase of Reynolds number.
5. The average friction factor decreases with increase in relative roughness pitch for relative roughness height and increases with the increase of relative roughness height for fixed value pitch.
6. Higher Nusselt number and thermal hydraulic performance were obtained for the Trapezoidal grooved tube compared with Circular, Square and plain tubes in the studied range of Reynolds number from 5000 to13500.
7. In triangular transverse wire rib, maximum value of f= 1.1066 when p= 4 and Re= 4000.
8. In the case of Equilateral triangular sectioned rib, for a given constant value of heat flux (1000 W/m2), the performance of the artificially roughened solar air heater is strong function of the Reynolds number, relative roughness pitch and relative roughness height.
9. In transverse rectangular rib, Stanton number increases with the Re. and thermo hydraulic performance parameter (ET) increases appreciably with the increase in the Re.
10. The maximum value of heat flux and friction factor observed with the Multi v-shaped ribs with gap as compare to the v-shape, multi v-shape and smooth surfaces.
11. Solar air heater gives the best performance with circular incline rib roughness geometry having relative inclination angle 0.666 and relative roughness height 0.0275.
12. When compared with the smooth duct, the presence of V-shaped blockages with perforation holes yields Nusselt number up to 6.38 times while friction factor rises up to 13.96 times.
13. The larger values of e/H and θ cause larger flow recirculation zones behind the Pentagonal shaped obstacles, resulting the larger pressure loss and produce a higher production rate of turbulent kinetic energy, and thus an enhanced heat transfer rate.
14. The heat transfer rate, which is more effective in V-down broken rib.
15. In the case Circular rib , Optimum value of Thermo-hydraulic performance parameter, which is 1.631, has been found corresponds to relative roughness height (e/D) of 0.042 and relative roughness pitch (P/e) of 10.714 for the Reynolds number of 15000.
16. The surface patterns with pyramids mounted at α = 45 generate stronger vortices and show the best overall efficiencies and Overall efficiency is improved by 12.0–169.4% compared to the plain channel.
17. In the case of Isosceles Right Triangle Rib , maximum thermo-hydraulic performance and Nusselt number is obtained for relative roughness pitch of 5 and relative roughness height 0.045.
18. CFD is an effective tool for predicting the behavior and performance of a solar air heater.
19. There is no doubt that a major focus of CFD analysis of solar air heater is to enhance the design process that deals with the heat transfer and fluid flow.

- **It is intended to study the Optimization of Thermal-Hydraulic Efficiency of Solar Air Heater by creating new rough geometry surface using CFD.**

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