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A Detailed Review on Artificial Roughness Geometries for Optimizing Thermo-Hydraulic Performance of Solar Air Heater

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Abstract: *It is well known fact that the heat transfer coefficient between the absorber surface of solar air collector & flowing fluid i.e. air can be improved by providing artificial roughness geometry on heat transfer surface (absorber surface).In this way the Thermal efficiency is increased. But at the same time due to roughness geometry pumping power of solar air collector in increased due to fictional losses in duct. So it necessary to examine the shape, size & flow pattern of various roughness elements to get maximum efficiency with minimum frictional losses. Therefore the selection of roughness geometry has to be based on the parameter that takes into account both Thermal & Hydraulic (friction) performance i.e. Thermo-hydraulic Performance of Solar air collector. Number of roughness elements has been investigated on heat transfer & friction characteristics of solar air collectors. In this paper, reviews of various artificial roughness elements used as passive heat transfer techniques, in order to improve Thermo-hydraulic performance of solar air collectors is reviewed & presented. Correlations developed by various researchers with the help of experimental results for heat transfer & friction factor for solar air collector by taking different roughness geometries are given & these correlations are useful to predict the Thermo-hydraulic performance of solar air collector having roughened ducts. The objective of this paper is also the awareness of effect of various types' roughness geometries on heat transfer & friction characteristics of solar air collectors for future researchers in simplified form.*

Keywords: *Artificial roughness, solar air heater, roughness geometry, Nusselt number, thermo hydraulic performance, Reynolds number, heat transfer coefficients, friction factor, aspect ratio.*

I. Introduction

Due to fast growing population & advance-ment in technology in each & every field such as Industrial, Agriculture & Research, energy is the prime requirement & the same trend will be increasing day by day. Conventional energy sources are exhaustible and are depleting fast. The present energy con-sumption is about 0.3 to 0.5 Q/Yr (1Q=1018 kJ) [1, 2], while as availability in the form of conventional energy resources such as coal, oil and natural gas is less. Conventional energy sources are not sufficient to meet the energy demands for very long. Besides, there is fear of possible environmental risks associated with the conventional fuels and nuclear energy. In early seventies the awareness of the limited nature of the reserves of fossil fuels resulted in sharp rise in the prices of these fuels. This came to be known as energy crisis. [3].This requires an urgent search of an alternate source of energy. Out of many alternatives, solar energy is most promising source due to

1. Free of cost
2. Pollution free
3. Presence on everywhere
4. Non exhaustive nature.

The drawback is it is location & time dependent. It requires efficient collection & storage systems for economical utilization point of view. Solar air heaters are the simplest & economical systems, which converts solar energy into the useful thermal energy & utilizes for various heating, cooling & drying applications. But the basic problems with solar air heaters are low thermal efficiency due to low heat transfer coefficient between absorber surfaces to air in the duct. There are various Active & passive methods to increase heat transfer coefficients. Using artificial roughness geometry on absorber surface exposed to air side in one of passive technique used by various researchers.

II. HISTORY OF ARTIFICIAL ROUGHNESS

The concept of artificial roughness was first applied by Joule [4] to enhance heat transfer coefficients for in-tube condensation of steam. Webb and Eckert [5] conducted experiential study of turbulent air flow in tubes roughened with rectangular repeated ribs and deduced heat transfer and friction factor correlations based on the law of wall similarity and application of the heat-momentum transfer analogy. Lewis [6] introduced new efficiency para-meter for optimizing thermohydraulic performance of roughened surfaces with respect to smooth surfaces. The experimental study carried out by Han [7-10] in search of the effect of rib shape, angle of attack, pitch to height ratio and spacing in square duct with two opposite rib roughened wall revealed that the maximum value of heat transfer and friction factor occurs for the ribs oriented at 45^o angle with a relative roughness pitch of 10. Ravigururajan and Bergles [11] developed general statistical correlations for heat transfer and pressure drop for single-phase turbulent flow in tubes roughened with semicircular, circular, rectangular and triangular shape ribs. Liou and Hwang [12] conducted experimental study on heat transfer and friction for turbulent flow through channel with two opposite walls roughened with semicircular, square and triangular shape ribs. Zhang et al. and Kiml et al. [13, 14] reported that the thermal per-formance of V-shaped ribs with 60o angle of attack is better than that of 45^o angle for the same range of flow parameters. Lau et al. [15] observed that the replacement of continuous transverse ribs by inclined ribs in a square duct results in higher turbulence near the roughened wall due to interaction of the primary and secondary flows which goes in favor of better thermal performance. Lau et al. [16, 17] studied the heat transfer and friction characteristics of fully developed flow in a square duct with transverse and inclined discrete ribs. Taslim et al. [18] and Olssom & Sunden [19] investigated the effect of V-shaped ribs in square channel and found fair enhancement in heat transfer as compared to inclined and transverse ribs. They observed that V-shaped ribs pointing downward have a much higher heat transfer coefficient because the warm air being pumped toward the rib leading region increases the apex region heat transfer coefficients as compared to that of the leading end region. Gao and Sunden [20] also reported that V-shaped ribs pointing downward perform better than the ribs pointing upward in rectangular ducts. A study by Hu and Shen [21] presented the effect of inclined discrete ribs with and without groove and revealed that the performance of inclined discrete rib without groove has been found best arrangement. In a recent study, Cho et al. [22] investigated the effect of a gap in inclined ribs on heat transfer for a fluid flow through square duct and reported that a gap in the inclined rib accelerates the flow and enhances the local turbulence, which results in an increase in the heat transfer.

They reported that the inclined rib with a downstream gap shows significant enhancement in heat transfer compared to that of continuous inclined rib arrangement. Moon et al. [23] investigated effect of channel height on heat transfer in a rectangular duct with a dimpled surface and observed enhancement in heat transfer by about 2.1 times regardless of channel height and friction factor of 1.6 - 2.0 times that of smooth channel. Mahmood and Ligrani [24, 25] measured local heat transfer on opposite walls with dimple type roughness with various temperature ratios having ratio of channel height to dimple print diameter of 0.5. They observed that the vortex structures augment local Nusselt number near downstream rim of each dimple. Burgess et al. [26] conducted an experimental study to investigate effect of dimple depth on heat transfer with aspect ratio of 8 and for Reynolds number range of 12000-70000 and reported that Nusselt number increases with increase in dimple depth. Sang et al. [27] investigated heat transfer with dimple/protrusion arrays in a rectangular duct with low Reynolds number range and observed heat transfer enhancement of 14 and 7 times for double protrusion wall and double dimpled wall at Reynolds number of 1000.

However at high Reynolds number of 10000, enhancement level observed was from 2 to 3. Chang et al. [28] examined heat transfer characteristics for four sets of dimpled channels with Reynolds number ranging from 1500 to 11000 and determined effect of dimpled arrangement, fin length to channel hydraulic diameter ratio and Reynolds number on heat transfer over the dimpled fin channel. Prasad and Mullick [29] were the first who introduced the application of artificial roughness in the form of small diameter wire attached on the underside of absorber plate to improve the thermal performance of solar air heater for drying purposes. Varun et al. [30], Hans et al. [31] , Bhushan et al. [32] ,A.K. Patil et al. [33], Pranab Kanti Roy [34] & Thakur Sanjay Kumar & NS Thakur [35] presented a review on roughness geometries used in solar air heaters wherein they discussed the outcomes of different studies concerning with heat transfer enhancement by the use of artificial roughness. Nikuradse (1950) [36] investigated the effect of roughness on the friction factor and velocity distribution in pipes which was roughened by sand blasting. Nunner (1958) [37] and Dippery and Sabersky (1963) [38] developed a friction similarity law and a heat momentum analogy for flow in sand grain roughened tubes. Donne and Meyer (1977) [39], Meyer (1982) [40], Wilkie (1966) [41], Sheriff and Gumley (1966) [42], Gomelauri (1964) [43], Wilkie and Mantle (1979) [44] & Vilemas and Simonis (1985) [45] investigated regular geometric roughness which can be produced in the form of cavities and ribs.

III. METHODOLOGY OF ARTIFICIAL ROUGHNESS

Whenever air flows over a heated surface, a very thin layer exists below the core turbulent region in which the flow remains predominantly laminar due to viscous effects called 'laminar sub layer'. Due to this viscous sub layer, the heat transfer rate from absorber surface to air is very low. Therefore the application of artificial roughness is to break that sub layer & creates local wall turbulence due to separation & reattachment of flow between two consecutive roughness elements. Thus turbulence created by various roughness elements significant enhances the heat transfer rates between the absorber surface & flowing fluid i.e. air.

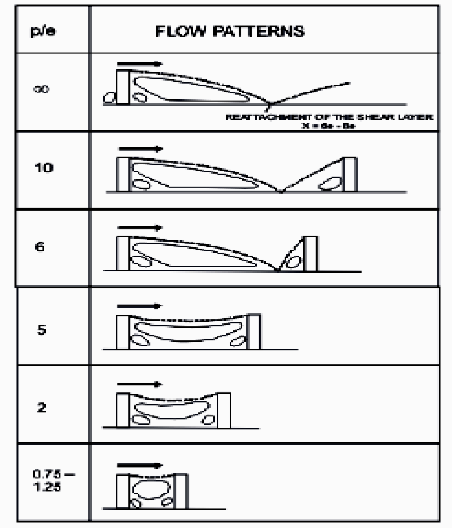

Fig. 1 Flow patterns downstream of wires with the roughness as a function of (p/e)
Source: Prasad & Saini (1988)

IV. ROUGHNESS PARAMETERS

1. Relative roughness height (e/D_H): It is the ratio of rib height (e) to equivalent diameter (D_H) of air passage.
2. Relative roughness pitch (p/e): It is the ration of distance between two consecutive ribs (p), height of rib (e).
3. Angle of attack (□): It is the inclination of the rib with the direction of air flow in the duct.
4. Aspect ratio: It is the ratio of duct width (W) to duct height (H).

V. EFFECT OF ROUGHNESS PARAMETERS

The effect of various roughness parameters & roughness geometry on heat transfer & friction factor is given below.

1. Effect of Reynolds Number

With the increases of Reynolds number, friction factor decreases due to the suppression of viscous sub-layer, whereas the Nusselt number increases with increases In Reynolds numbers because it is nothing but the ratio of conductive resistance to convective resistance of heat flow and as Reynolds member increases thickness of boundary layer decreases & hence convective resistance decreases which in turn increases the Nusselt number.

2. Effect of rib

The effect of rib is the most important that produced on the flow pattern; it generates two separate regions of the flow, one on each side of the rib. The turbulence occurs by the generation of the vortices and hence the enhancement in heat transfers as well as in the friction losses takes place.

3. Angle of attack (□)

Various researchers have investigated exp-erimentally, the effect of angle of attack *(α)* on the flow pattern. Besides the relative roughness height (e/D_H) & relative roughness pitch (p/e), the most important parameter is angle of attack *(α)* with respect to rib position. The inclined ribs gives a higher heat transfer rate that the transverse rib because of the secondary flow induced by the rib, in addition to breaking the viscous sub layer and producing local wall turbulence.

4. Effect of Relative roughness height (e/D_H)

Fig. 1 (Prasad & Saini, 1988) & Fig. 2 (Prasad & Saini, 1991) [47] depict the flow pattern downstream of a rib & effect on the laminar sub layer as the rib height is changed respectively. Breakage ofviscous sub layer due to repeated ribs increases the rate of heat transfer by creating local wall turbulence. If the ribs protrude beyond the viscous sub layer, they would increase the heat transfer rate, but also causes much higher frictional losses. Optimal thermo -hydraulic performance conditions are obtained when the roughness height is slightly higher than the transition sub layer thickness (Prasad & Saini, 1991). Table 1 shows the values of Relative roughness height (e/D_H) for a maximum value of heat transfer coefficient.

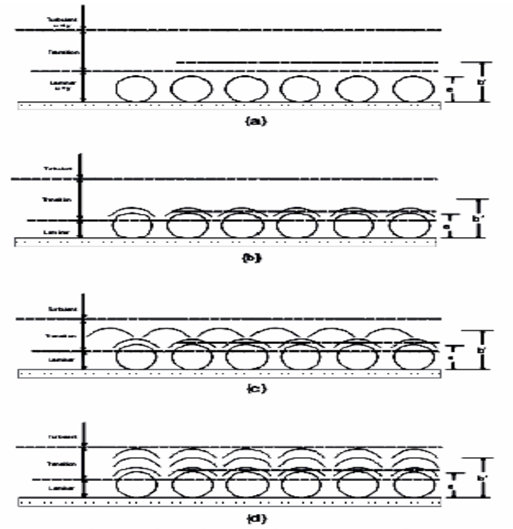

Fig. 2 Roughness heights with respect to laminar sub layer
Source: Prasad & Saini (1991)

5. Effect of Relative roughness pitch (p/e)

Various researchers have shown the effect of a relative roughness pitch (p/e) on the flow pattern i.e. heat transfer coefficient & fiction factor. Table 2 shows the values of relative roughness pitch (p/e) for a maximum value of heat transfer coefficients for different types of artificial roughness. Fig. 3 (Prasad & Saini, 1988) depicts the flow pattern downstream from a rib as a function of a relative roughness pitch (p/e). Due to separation at the rib, reattachment of the free shear layer does not occur for a relative roughness pitch (p/e) less than about 8 to 10. The maximum heat transfer coefficient occurs in the vicinity of the reattachment point. For relative roughness height (p/e) less than 8 to 10, reattachment will not occur, which results in the decrease of heat transfer rate. The rate of increase in friction factor will increase with the decrease of pitch. However, an increase in the relative roughness pitch (p/e) beyond 10 resulted in the decrease of heat transfer enhancement.

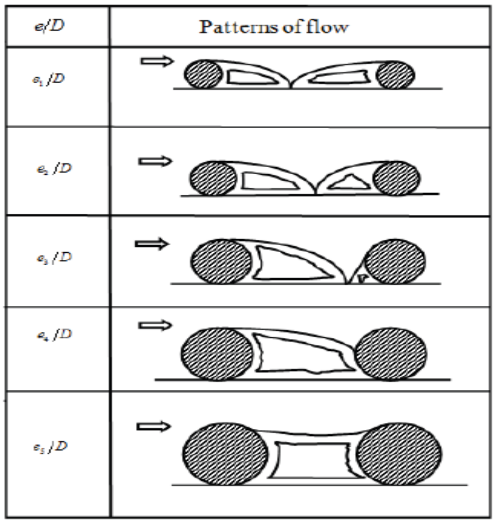

Fig. 3 Flow patterns downstream of ribs with the roughness as a function of (e/D_H)
Source: Prasad & Saini (1988)

VI. Vi. EXPERIMENTAL APPROACH

An experimental investigation has been planned to generate data on heat transfer coefficient and friction factor that can be utilized to develop heat transfer and friction factor correlations. It is proposed to collect data on heat transfer coefficient and friction factor as function of roughness parameters (relative roughness height), aspect ratio of duct and Reynolds number of flow. Experimental data have also been collected on a smooth duct under similar geometrical and flow conditions in order to have a direct comparison of the performance of the roughened duct with that of a conventional smooth rectangular duct flow with respect to heat transfer and fluid flow characteristics. And to ensure the reliability of experimental data it is necessary to perform experimentation on validated experimental set as per guidelines of ASHARE standards 93-77 [46] under standard test conditions.

TABLE 1: VALUES OF RELATIVE ROUGHNESS HEIGHT (e/D_H) FOR A MAXIMUM VALUE OF HEAT TRANSFER COEFFICIENT FOR DIFFERENT ROUGHNESS GEOMETRIES USED IN SOLAR AIR HEATER DUCT

S. N	**Investigators**	**Roughness geometry**	**Value of (e/D_H) for max heat transfer coeff.**
1	Prasad & Saini (1988)	Wire	0.033
2	Karwa et al. (2001)	Chamfered rib	0.0441
3	Momin et.al. (2002)	V-Shaped rib	0.034
4	Bhagoria et.al. (2002)	Transverse wedge	0.033
5	Jaurker et.al. (2006)	Transverse rib-grooved	0.036
6	Karmare & Tikekarv (2007)	Metal grit rib roughness	0.044
7	Layek et.ala.(2007)	Transverse chamfered rib grooved	0.04
8	Saini & Verma (2008)	Dimple shape roughness	0.0379
9	Saini & Saini (2008)	Arc shaped wire	0.0422

TABLE 2: VALUES OF RELATIVE ROUGHNESS PITCH (p/e) FOR A MAXIMUM VALUE OF HEAT TRANSFER COEFFICIENT FOR DIFFERENT ROUGHNESS GEOMETRIES USED IN SOLAR AIR HEATER DUCT

S. N	**Investigators**	**Roughness geometry**	**Value of (p/e) for max heat transfer coeff.**
1	Prasad & Saini (1988)	Wire	10
2	Karwa et al. (2001)	Chamfered rib	7.09
3	Bhagoria et.al. (2002)	Transverse wedge	7.57
4	Sahu & Bhagoria (2005)	90^0 broken transverse	13.33
5	Jaurker et.al. (2006)	Transverse rib-grooved	6
6	Karmare & Tikekarv (2007)	Metal grit rib roughness	17.5
7	Layek et.ala.(2007)	Transverse chamfered rib grooved	6
8	Varun et.al.(2008)	Combination of inclined & transverse ribs	8
9	Saini & Verma (2008)	Dimple shape roughness	10

VII. Main Elements Of Experimental Setup

The main elements of Experimental set up comprises of insulated rectangular duct with metallic artificially roughened absorber plate. Uniform heat flux in supplied over the top surface of the plate by means of electric heater and bottom surface is modified by providing artificial roughness elements. The duct has inlet section, test section & exit section. The test section consists of a micro manometer to measurement of Pressure drop. The duct is connected to a circular pipe which includes flow measurement device (inclined U tube manometer) & flow control valve. The other end of the pipe is connected to the suction side of a centrifugal blower which exhales the air to the surroundings thus forming an open loop system.

VIII. Experimental Procedure

All components of the experimental setup and the instruments have been checked for proper operation.

The blower is then switched on and the joints of the setup are checked for air leakage with soap bubble technique. Micro manometer and inclined U-tube manometer are properly leveled. Blower is switched on and the flow control valve is adjusted to give a predetermined rate of airflow to the test section. The test runs to collect relevant heat transfer and flow friction data were conducted under quasi-steady state conditions. The quasi-steady state condition is assumed to have been reached when the temperature at a point does not change for about 10-12 minutes. When a change in the operating conditions is made, it takes about 30-40 minutes to reach such a quasi-steady state. After each change of flow rate, the system was allowed to attain a steady state before the data were recorded. In order to reduce the effect of inaccuracy in the measurement of temperature, this strongly affects the accuracy of the calculation of the heat transfer coefficient, the temperature of the air through the duct has been maintained greater than 10^{o}C and the temperature difference between the heated plate and the bulk air temperature has been kept above 20^{0}C. During the experimentation the temperature of air entering the duct ranges between.

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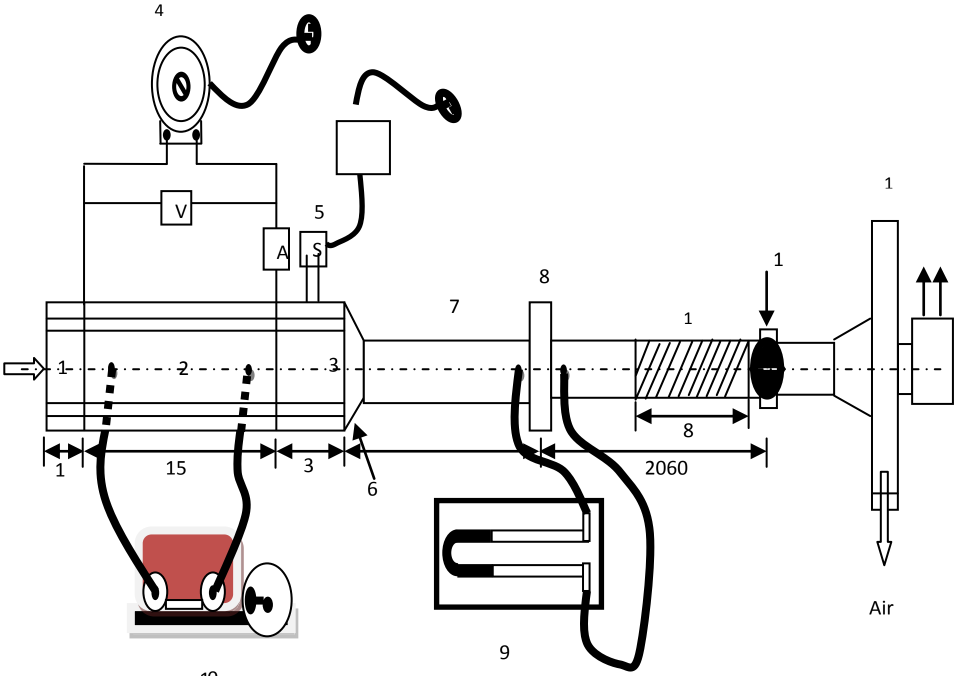

Fig. 4 Schematic diagrams showing top view of Indoor experimental Setup

(1) Air inlet section (2) Test section (3) Air outlet section (4) Variac (5) Selector switches (6) Mixing section (7) G.I. pipe (8) Orifice plate (9) Inclined U tube (10) Micro manometer (11) Flow control (12) Flexible pipe (13) Blower

30°C to 40°C according to the local atmospheric conditions. The temperature of the air at the outlet of the test section ranges between about 40°C to 65°C. All readings have been noted under steady state condition which was assumed to have been obtained when the plate and air outlet temperature did not deviate over a 15 min. period. After the steady state has reached, the heater assembly voltage and current, the plate temperatures, the inlet and exit air temperatures and the pressure drop across the duct and across the orifice plate have been recorded. For each rib configuration 6 runs have been conducted at air-flow rates corresponding to the flow Reynolds numbers between 3000 and 15000. The following parameters were measured during the experiments.

1. Pressure drop across the orifice plate & duct by inclined U- tube & micro manometer
2. Inlet air temperature of collectors by using digital multimeter and thermocouples.
3. Outlet air temperature of collectors
4. Temperature of plate

IX. Various Roughness Geometries Used in Solar Air heater

1. Transverse ribs in the form of small diameter wires

Prasad & Saini [48] investigated the effect of protrusions from underside of absorber surface in the form of small diameter wires on heat transfer & friction factor for fully developed turbulent flow in a solar air heater duct. As shown in Fig.5.

Range of Parameters:

1. p/e ---10, 15, 20
2. e/D_H---0.020,0.027,0.033

Results: Both Nusselt number & Friction factor increases with e/D_H, but the rate of heat transfer enhancement diminishes with increase in $e/D_{H,}$ while the rate of increase of friction factor was found to be nearly constant. The maximum value of Nusselt number & Friction factor were reported to be 2.38 & 4.25 respectively at the p/e = 10.

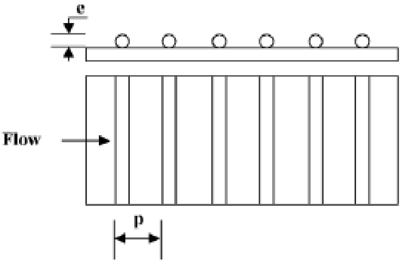

Fig. 5 Transverse ribs

2. Transverse & inclined ribs in the form of small diameter wires

Gupta et al. (1993) [49] investigated the effect of transverse & inclined wire roughness on fluid flow characteristics & heat transfer & friction factor for solar air heater. As shown in Fig.6.

Range of Parameters:

1. p/e:7.5 & 10
2. e/D_H:0.020-0.053
3. α: 30^0-90^0
4. Re: 5000-30000

Results: It was found that the heat transfer coefficient in roughened duct could be improved by a factor up to 1.8 & the friction factor had been found to increase by a factor of 2.7 times of smooth duct. The maximum heat transfer coefficient & friction factor were found at an angle of attack of 60^0 & 70^0 respectively in the range of parameters investigated. The thermo-hydraulic performance of roughened surface has been found best corresponding e/D_H = 0.033 & the Reynolds number corresponding to the best thermo-hydraulic performance were around 14000 in the range of parameters investigated. The investigation emphasized that the secondary flow rolling along the inclined rib is responsible for higher heat transfer rates.

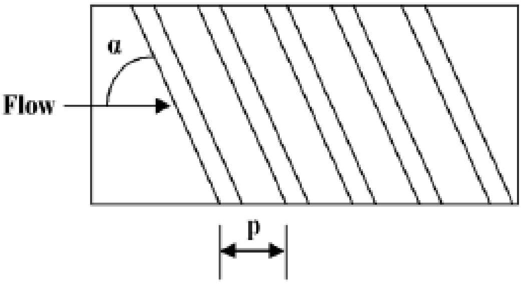

Fig. 6 Inclined ribs

3. Broken transverse rib roughness

Sahu & Bhagoria [50] varied the pitch for 90^0 broken transverse rib roughness & examined its effect on thermal performance of solar air heater. As shown in Fig.7.

Range of Parameters:

1. Re:3000-12000
2. p: 10-30 mm
3. e: 1.5 mm
4. W/H: 8

Results: The Nu increases sharply at low Re & remains constant for higher Re. The maximum enhancement of heat transfer was reported at the p=20 mm. It has been highlighted that smooth duct performs better than the roughened duct at Re below 5000. Experimental results revealed that roughened absorber plates increases the heat transfer coefficient 1.25-1.4 times as compared to smooth rectangular duct & maximum efficiency of roughened solar air heater lying in the range of 51-83.5%, depending upon the flow conditions.

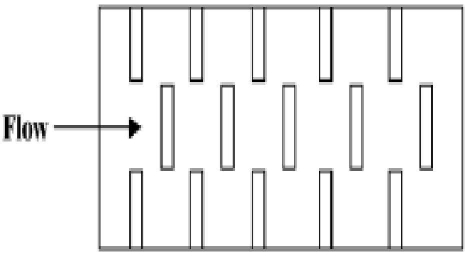

Fig. 7 Broken transverse ribs

4. Inclined broken rib roughness

Aharwal et al. [51] experimentally studied the heat transfer and friction factor of a rectangular duct roughened with repeated ribs with a gap & at an inclination with respect to the flow direction. As shown in Fig.8.

Range of Parameters:-

1. Re:3000-18000
2. Relative gap position: 0.16-0.5
3. Relative gap width: 0.5-2
4. W/H: 5.84
5. p/e:4-10
6. e/D_H:0.018-0.037
7. α: 30^0-90^0

Results: Maximum enhancement in Nu, f & thermo-hydraulic performance are 2.83, 2.89 & 1.97 times respectively as compared to smooth duct in the range of parameters investigated. The Nu & f were found to be highest corresponding to a relative gap position of 0.25 & a relative gap width of 1. It was found that below & beyond the relative gap width of value 1 reduces the heat transfer rates. It was found that due to gap in inclined rib the secondary flow along the rib joins the main flow through gap accelerating the flow field behind the rib, which energies the retarded boundary layer flow along the surface & enhances the heat transfer rates.

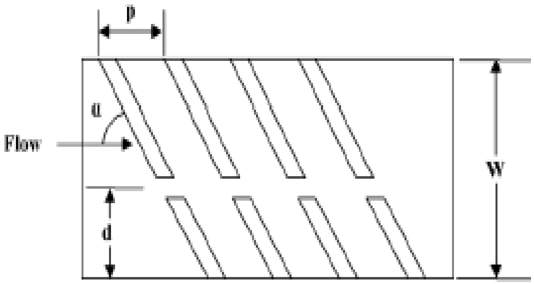

Fig.8 Inclined broken ribs

5. Combined inclined & transverse rib roughness

Varun et al. [52] experimentally investigated the combined inclined & transverse rib roughness geometry and studied its effect on the thermal performance. As shown in Fig.9.

Range of Parameters:-

1. Re:2000-14000
2. p/e: 3-8
3. e/D_H: 0.03
4. W/H: 10

Results: -It is found that the maximum thermal efficiency occurs at relative roughness pitch (p/e) of 8.

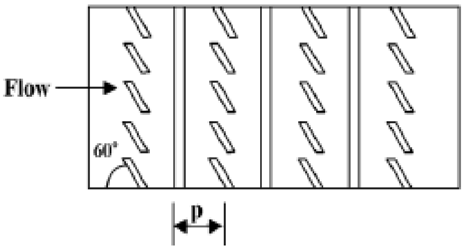

Fig. 9 Combined inclined & transverse ribs

6. Rib grooved roughness

Jaurker et al. [53] experimentally generated the friction & heat transfer data for turbulent flow through a rectangular duct with rib-grooved transverse repeated rib roughness produced on one broad heated wall. As shown in Fig.10.

Range of Parameters:-

1. Re:3000-21000
2. p/e: 4.5-10
3. e/D_H: 0.0181-0.0363
4. g/p: 0.3-0.7

Results: - Nu & friction factor increases up to 2.7 & 3.6 times as compared to smooth surface in the range of parameters investigated. The maximum heat transfer &friction factor were observed at p/e =10 & relative groove position of 0.4.The additional vortices in & around the grooves were found to be responsible for the higher turbulence intensity between the ribs results in higher heat transfer rates.

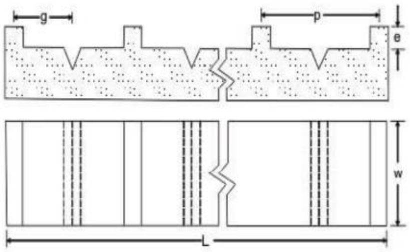

Fig. 10 Rib grooved roughness

7. Repeated chamfered rib roughness

Karwa et al. (1999) [54] experimentally found the effect of rib head chamfer angle (Φ) & duct aspect ratio heat transfer & friction factor in a rectangular duct roughened with integral chamfered ribs. As shown in Fig.11.

Range of Parameters:-

1. Re:3000-20000
2. p/e: 4.5,5.8,7,8.5
3. e/D_H: 0.014-0.0328
4. W/H: 4.8,6.1,7.8,9.66,12
5. Φ: $-15^0, 0^0, 10^0, 15^0, 18^0$

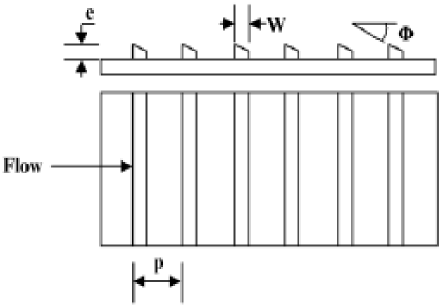

Fig. 11 Repeated chamfered ribs

Results: - As compared to smooth plate 2 & 3 times Stanton number & friction factor increases respectively in the range of parameters investigated. The highest heat transfer & friction factor exists for a chamfer angle (Φ) of 15^0. The minima of heat transfer function occur at roughness Reynolds number of about 20. The heat transfer function increases with the increase in the aspect ratio from 4.65-9.66 & the roughness function decreases with the increase in the aspect ratio from 4.65-7.75 & therefore both the functions attain nearly a constant value. It has been pointed out that positive chamfer encourages the frequent shedding of vortices causing greater heat removal from the surface & higher frictional losses while in case of negative chamfer.

8. V shaped rib roughness

Momin et al. (2002) [55] experimentally in-vestigated the effect of V shaped ribs on heat transfer & fluid flow characteristics in rectangular duct of solar air heater. As shown in Fig.12.

Range of Parameters:-

1. Re:2500-18000
2. p/e: 10
3. e/D_H: 0.02-0.034
4. α: 30^0-90

Results: - Friction factor increases more rapidly than Nu with the increase of Re because the reattachment of free shear layer might not occur at higher Reynolds number. The maximum enhancement in Nu & Friction factor had been found 2.3 & 2.83 times respectively as compared to smooth surface for an angle of attack of 60^0.It was also found that for e/D_H=0.034 & α=60^0, the V shaped ribs enhances the value of Nu by 1.14 & 2.3 times over inclined ribs & smooth plate respectively. It was concluded that V shaped ribs gave better heat transfer performance than the inclined ribs for similar operating conditions.

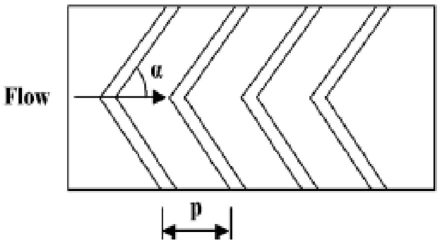

Fig.12 V shaped ribs

9. Staggered discrete V apex up & down rib roughness

Muluwork et al. (1998) [56] compared the thermal performance of staggered discrete V apex up & down with corresponding transverse staggered discrete ribs. The relative roughness length ratio had been considered as dimensionless geometric parameters of roughness element to compare three distinct configurations. As shown in Fig.13.

Range of Parameters:-

1. Re:2000-15500
2. B/S: 3-9
3. e/D_H: 0.02
4. α: 60^0

Results: -The Stanton number & friction factor increases with the increase of relative roughness length ratio. The Stanton number for V down discrete ribs was higher than the corresponding V up & transverse discrete ribs. The Stanton number ratio enhancement was found 1.32-2.47 in the range of parameters investigated. Further for Stanton number, it was seen that the ribbed surface friction factor for V down discrete ribs was highest among the three configurations investigated.

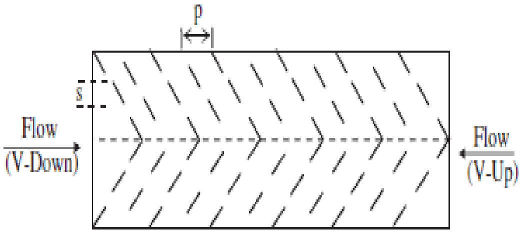

Fig. 13 Staggered discrete V apex up & down ribs

10. Transverse, Inclined, V-continuous & V-discrete rib roughness

Karwa [57] experimentally investigated heat transfer & friction factor in a high aspect ratio duct with transverse, Inclined, V-up & down continuous, V-up & down discrete ribs. As shown in Fig.14.

Range of Parameters:-

1. p/e: 10
2. B/S: 3
3. e/D_H: 0.0467-0.05
4. α: 60^0-90^0
5. W/H: 7.19-7.75

Results: -The enhancement in Stanton number of transverse, Inclined, V-up continuous, V- down continuous, V-up discrete & V-down discrete ribs over smooth duct was found to be 65-90%, 87-112%, 102-137%, 110-147%, 93-134%, 102-142% respectively. Study reveals that the V-down discrete ribs secured the best thermal performance for the same power consumption. The study also emphasized that discrete ribs have lower friction losses as compared to continuous ribs due to change in flow behavior.

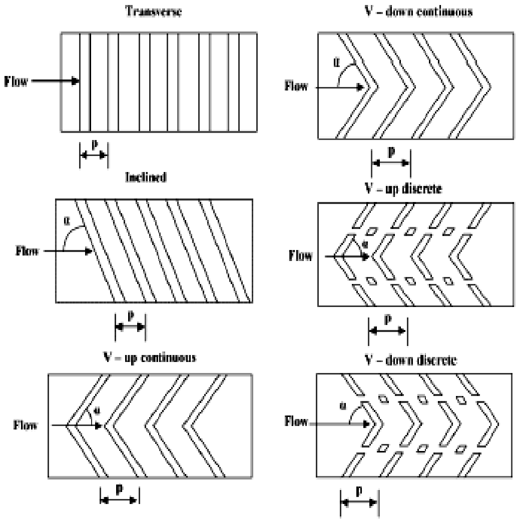

Fig. 14 transverse, Inclined, V-up continuous, V- down continuous, V-up discrete & V-down discrete ribs

11. Multi V rib roughness

Hans et al. [58] recently experimentally studied the heat transfer& friction factor characteristics in a multi V rib roughened roughness. As shown in Fig.15.

Range of Parameters:-

1. Re:2000-20000
2. p/e: 6-12
3. e/D_H: 0.019-0.043
4. α: 30^0-75^0
5. W/w: 1-10

Results: -Maximum enhancement in Nu & f has found to be 6 &5 times respectively in comparison to smooth duct. The maximum value of heat transfer & friction factor has been found at relative roughness width (W/w) of 6 & 10 respectively. Beyond that heat transfer decreases & friction factor again increases both due to separation of flow. Also found that maximum Nu & f occurs at $\alpha=60^0$.

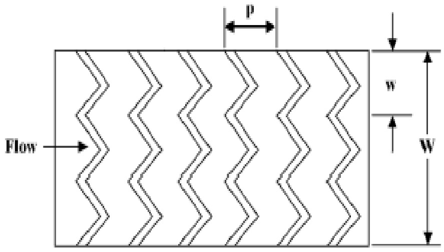

Fig. 15 Multi V rib roughness

12. Discrete W-shape rib roughness

Kumar et al. [59] investigated the heat transfer friction characteristics of W shape discrete ribs in solar air heater. As shown in Fig.16.

Range of Parameters:-

1. Re:3000-15000
2. p/e: 10
3. e/D_H: 0.0168-0.0338
4. α: 30^0-75^0

Results: - The maximum enhancement of Nu & f was found reported as 2.16 & 2.75 times respectively that of smooth duct for $\alpha=60^0$ & $e/D_H=0.0338$.Studied shows that the enhancement of V shape ribs is based on observation of the creation of secondary flow cell due to inclination of rib resulting in a region of high heat transfer near the leading edge & one trailing edge, & thus develops a region of almost double heat transfer rate. Therefore W shape roughness gives better performance than the V shape roughness since its leading is more than trailing edge.

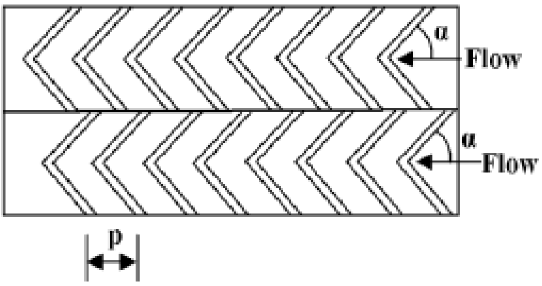

Fig. 16 Discrete W shape rib roughness

13. W-up & W-down rib roughness

Lanjewar et al. [60] reported the heat transfer & friction characteristics with W-shape ribs pointing downstream & upstream. As shown in Fig. 17 & 18.

Range of Parameters:-

1. Re:2300-14000
2. p/e: 10
3. e/D_H: 0.033
4. α: 45^0
5. W/H: 8

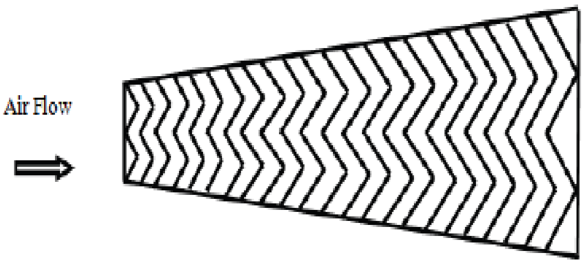

Fig. 17 W-down rib roughness

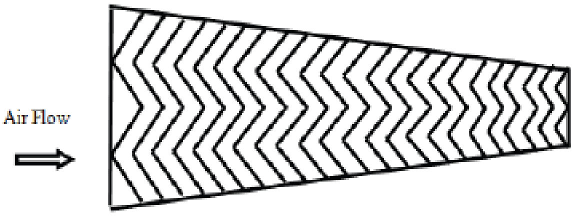

Fig. 18 W-up rib roughness

Results: -The enhancement of heat transfer by providing W-shape ribs is 2.39 for W-down & 2.21 for W-up than the smooth duct. Also found that W-down ribs give better thermo-hydraulic performance than W-up & V ribs. The maximum thermo-hydraulic performance for W-down ribs is 1.98 while it is 1.81 for W-up ribs in the range of parameters investigated.

14. Arc shape rib roughness

Saini & Saini [61] investigated the heat transfer & fluid characteristics of arc shape roughness of a solar air heater duct. As shown in Fig.19.

Range of Parameters:-

1. Re:2000-17000
2. p/e: 10
3. e/D_H: 0.0213-0.0422
4. relative angle of attack ($\alpha/90$): 0.333-0.666
5. W/H: 12

Results: - The maximum enhancement in Nu has been obtained as 3.80 times that of smooth duct for relative angle of attack ($\alpha/90$) of 0.333 & relative roughness height e/D_H of 0.0422. However the increment in friction factor corresponding to these parameters has been observed 1.75 times only.

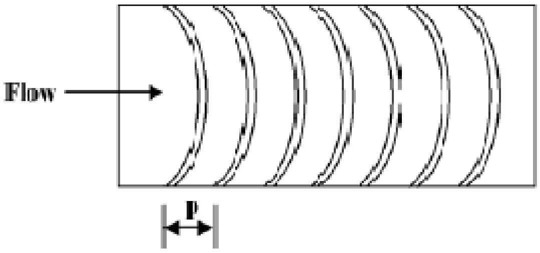

Fig. 19 Arc shape rib roughness

15. Wedge shape rib roughness

Bhagoria et al. [62] experimentally studied the heat transfer & fluid flow characteristics of transverse wedge shape ribs. As shown in Fig.20.

Range of Parameters:-

1. Re:3000-18000
2. p/e: 5.67,7.57,10,12.1
3. e/D_H: 0.015-0.033
4. α: 90^0
5. ø: 8,10,12,15

Results: - The maximum heat transfer occurs at a wedge angle (ø) of about 10, while on either side of this angle, Nu decreases. The friction factor increases as the wedge angle increases. The heat transfer & friction factor are 2.4 & 5.3 times of smooth duct at p/e of about 7.57. Studied shows that wedge shape ribs showed significant enhancement in heat transfer over square & chamfered ribs due to relatively lesser chances of eddy formation downstream of ribs.

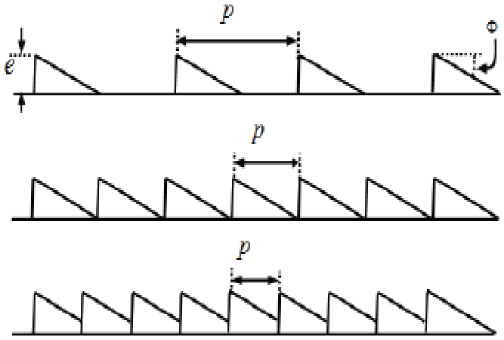

Fig.20 Wedge shape rib roughness

16. Dimple shape rib roughness

Saini & Verma [63] studied experimentally the effect of protrusion dimple shape of heat transfer & fluid flow characteristics. As shown in Fig.21.

Range of Parameters:-

1. Re:2000-12000
2. p/e: 8-12
3. e/D_H: 0.018-0.037

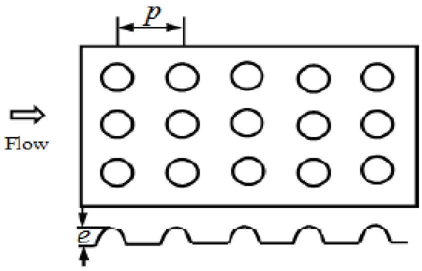

Fig. 21 Dimple shape rib roughness

Results: - The maximum heat transfer occurs at relative roughness height of 0.0379 & relative roughness pitch of 10.The friction factor is minimum corresponding to relative roughness height of 0.0289 & relative roughness pitch of 10.

17. Chamfered rib grooved roughness

Layek et al. [64] investigate experimentally the heat transfer & friction characteristics with repeated integral transverse chamfered rib with groove. As shown in Figure 22.

Range of Parameters:-

1. Re:3000-21000
2. p/e: 4.5-10
3. e/D_H: 0.022- 0.04
4. relative grove position(g/p):0.3-0.6
5. chamfer angle (ϕ): 5^0-30^0

Results: -For p/e=6,g/p=0.4, ϕ $=18^0$ & e/D_H=0.04 the enhancement in Nu is 3.24 times the smooth duct at Re=21000 while friction factor is of 3.78 times.

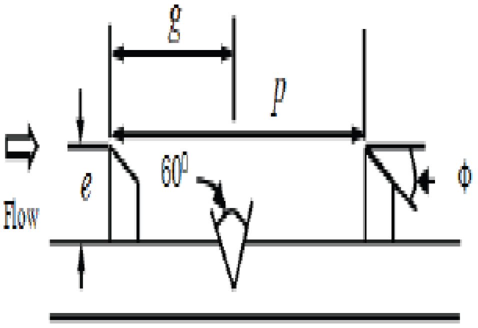

Fig.22 Chamfered ribs with groove roughness

18. Expanded metal mesh roughness

Saini & Saini [65] investigated experimentally the heat transfer & fiction characteristics for flow inside a large aspect ratio duct n the form of expanded metal mesh. As shown in Fig.23.

Range of Parameters:-

1. Re:1900-13000
2. L/e: 25-71.87
3. S/e: 15.62-46.87
4. e/D_H: 0.012- 0.039

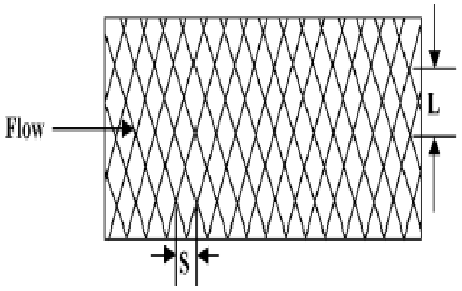

Fig. 23 Wire mesh roughness

Results: -The average Nusselt number attains maximum value at the relative longway length of mesh (L/e) of 46.87 & relative shortway length (S/e) of 25 at α= 72^0 for relative longway length of 71.87 & relative shortway length of 15.62. The maximum enhancements in Nu & friction factor were found to be 4 & 5 times to the smooth plate respectively.

19. Metal grit ribs roughness

Karmare & Tikekar et al. [66] experimentally investigated the thermal performance of solar air duct with metal grit ribs roughness. As shown in Fig.24.

Range of Parameters:-

1. Re:4000-17000
2. Relative roughness height of grid(e/D_H): 0.035-0.044
3. Relative roughness pitch of grid (p/e): 12.5-36
4. Relative length of metal grit (l/s):1-1.72

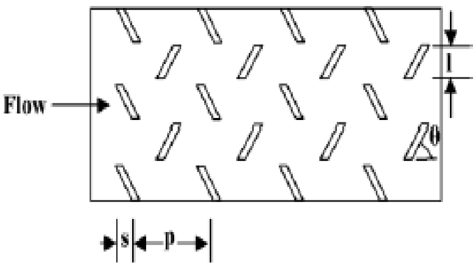

Fig. 24 Metal grit rib roughness

Results: -The enhancement in Nusselt number & friction factor was observed about (187%-200%) & (213%-300%) respectively as compared to smooth. The maximum heat transfer rate & optimum thermal hydraulic performance occurred for l/s=1.72, e/D_H =0.044 & p/e= 17.5.Similarly the maximum friction factor occurred for l/s=1.72, e/D_H =0.044 & p/e= 12.5.

20. Inverted U shape turbulators roughness

Bopche & Tandale [67] investigated experimentally the heat transfer & friction factor characteristics for inverted U shape turbulators in solar air heater. As shown in Fig.25.

Range of Parameters:-

1. Re:3800-18000
2. (e/D_H): 0.0186-0.03986
3. Turbulator pitch to height (p/e): 6.67-57.14
4. α: 90^0

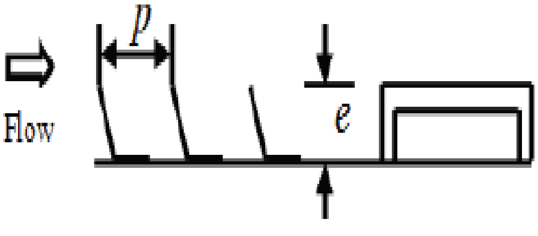

Fig. 25 Inverted U shaped turbulators

Results: -The inverted U shape turbulators showed appreciable heat transfer enhancement even at low Reynolds number (Re< 5000) where ribs were inefficient. The maximum enhancement in Nusselt number & friction factor compared to smooth duct were of the order of 2.82 & 3.72 respectively. Studied shows that turbulence generated only in the viscous sub layer region of the boundary layer resulted in better thermo-hydraulic performance i.e. maximum heat transfer enhancement at an affordable friction penalty.

References

[1] Hsieh, J.S., Solar Energy Engineering, Prenticed Hall Inc., New Jersey, 1986
[2] Veziroghu, T.N., Solar Energy International Progress, Pergamon Press, 1,167-173, 1980
[3] Sukhatme S.P., "Solar Energy: Principles of Thermal Collections and Storage", Tata McGraw-Hill, New Delhi 1994.

[4] Joule J.P., "On the surface condensation of steam", Philos Trans R Soc Lond, 151, 133-160, 1861.

[5] Webb R.L., Eckert E.R.G. and Goldstein R. J., "Heat transfer and friction in tubes with repeated rib roughness", International journal of Heat mass transfer, 14, 601-617, 1971.

[6] Lewis M.J., "Optimizing the thermohydraulic performance of rough surfaces". International journal of Heat mass transfer, 18, 1243-1248, 1975.

[7] Han J.C., Glicksman L.R., Rohsenow W.M., "Heat transfer and friction for rib roughened surfaces", International journal of Heat mass transfer, 21, 1143-1156, 1978.

[8] Han J.C., "Heat transfer and friction in channels with opposite rib roughened walls", Trans. ASME Journal of Heat Transfer, 106, 774-781, 1984.

[9] Han J.C., Park J.S., "Developing heat transfer in a rectangular channel with rib turbulators", Trans. ASME Journal of Heat Transfer, 31, 183-195, 1988.

[10] Han, J.C., Park, J.S., Lei, C.K., "Augmented heat transfer in rectangular channel of narrow aspect ratios with rib turbulators", International journal of Heat mass transfer, 32/9, 1619-1630, 1989.

[11] Ravigururajan T.S., Bergles A.E., "General correlations for pressure drop and heat transfer for single-phase turbulent flow in internally ribbed tubes", J. ASME, 52, 9-20, 1985.

[12] Liou T.M., Hwang J.J., "Effect of ridge shapes on turbulent heat transfer and friction in a rectangular channel", International Journal of Heat and Mass Transfer, 36, 931−940, 1993.

[13] Han J.C., Zhang Y.M., "High performance heat transfers ducts with parallel broken and V- shaped broken ribs", International journal of Heat mass transfer, 35(2), 513-523, 1992.

[14] Kiml R., Mochizuki S., Murata A., "Effects of rib arrangements on heat transfer and flow behavior in a rectangular rib roughened passage", International Journal of Heat and mass transfer, 123, 675-681, 2001.

[15] Lau S.C., McMillin R.D., Han J.C., "Turbulent heat transfer and friction in a square channel with discrete rib turbulators", Trans. ASME Journal of Turbo machinery, 113, 360-366, 1991.

[16] Lau S.C., McMillin R.D., Han J.C., "Heat transfer characteristics of turbulent flow in a square channel with angled rib", Trans. ASME Journal of Turbo machinery, 113, 367-374, 1991.

[17] Lau S.C., Kukreja R.T., McMillin R.D., "Effects of V shaped rib arrays on turbulent heat transfer and friction of fully developed flow in a square channel", International Journal of Heat and mass transfer, 34,1605-1616, 1991.

[18] Taslim M.E., Li T., Kercher D.M., "Experimental heat transfer and friction in channels roughened with angled, V-shaped and discrete ribs on two opposite walls", Trans. ASME Journal of Turbo machinery, 118, 20-28, 1996.

[19] Olsson C.O., Sunden B., "Thermal and hydraulic performance of a rectangular duct with multiple V-shaped ribs", Trans. ASME, 120, 1072-1077, 1998.

[20] Gao X., Sunden B., "Heat transfer and pressure drop measurements in rib roughened rectangular ducts", Exp. Thermal Fluid Sci., 24, 25-34, 2001.

[21] Hu Z., Shen J., "Heat transfer enhancement in a converging passage with discrete ribs", International Journal of Heat and mass transfer, 39(8), 1719-1727, 1996.

[22] Cho H.H., Kim Y.Y., Rhee D.H., Lee S.Y., Wu S.J., "The effect of gap position in discrete ribs on local heat/mass transfer in a square duct", Journal of Enhanced Heat Transfer, 10(3),287-300, 2003.

[23] Moon H.K., O'Connell T., Glezer B., "Channel height effect on heat transfer and friction in a dimpled passage", ASME Journal Eng. Gas Turbines Power, 122(2), 307-313, 2000.

[24] Mahmood G.I., Hill M.L., Nelson D.L., Ligrani P.M., Moon H.K., Glezer B., "Local heat transfer and flow structure on and above a dimpled surface in a channel", Trans. ASME Journal of Turbo machinery, 123, 115, 2001.

[25] Mahmood G.I., Ligrani P.M., "Heat transfer in a dimpled channel: combined influences of aspect ratio, temperature ratio, Reynolds number and flow structure", International Journal of Heat and mass transfer, 45, 2011-2020, 2002.

[26] Burgess N.K., Oliveira M.M., Ligrani P.M., "Nusselt number behavior on deep dimpled surfaces within a channel", Journal of Heat Transfer, 125, 11-18, 2003.

[27] Sang D.H., Hyun G.K., Hyung H.C., "Heat transfer with dimple/protrusion arrays in a rectangular duct with low Reynolds number range", Int J Heat Fluid Flow, 29,916-926, 2008.

[28] Chang S.W., Chiang K.F., Yang T.L., Huang C.C., "Heat transfer and pressure drop in dimpled fin channels", Experimental thermal and fluid science, 33(1),23-40, 2008 .

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

[30] Varun, Saini R.P., Singal S.K., "A review on roughness geometry used in solar air heaters", Solar Energy, 81, 1340-1350, 2007.

[31] Hans V.S., Saini, R.P., Saini, J.S., "Performance of artificially roughened solar air heaters-A review", Renewable and Sustainable Energy Reviews, 13, 1854-1869, 2009.

[32] Bhushan B., Singh R., "A review on methodology of artificial roughness used in duct of solar air heaters", Energy, 35, 202-212, 2010.

[33] A.K. Patil, J.S. Saini, K. Kumar," A Comprehensive Review on Roughness Geometries and Investigation Techniques Used in Artificially Roughened Solar Air Heaters",IJRER,Vol.2, No.1, 2012.

[34] Pranab Kanti Roy & Kisalaya Chakrabarti, "A review on Heat transfer & friction factor characteristics of artificial roughened solar air heater duct", Asian Journal of Science and Technology Vol. 4, Issue 07, pp. 045-056, July, 2013

[35] Thakur Sanjay Kumar, N S Thakur, Anoop Kumar, Vijay Mittal," A review on use of artificial roughness to enhance heat transfer in solar air heaters", Journal of Energy in Southern Africa • Vol 21 No 1 • February 2010

[36] Nikuradse, J., 1950.Laws of flow in rough pipes. NACA, Technical Memorandum 1292. Nov 1950.

[37] Nunner, W, 1958 [A5]. Heat transfer and pressure drop in rough tubes. VDI Forch 445-B 5-39 (1956); AERE Lib Trans. 786.

[38] Dippery, D.F., Sabersky, R.H., 1963. Heat and momentum transfer in smooth and rough tubes at various Prandtl number. International Journal Heat and Mass Transfer 6, 329–353.

[39] Donne, D., Meyer, L., 1977.Turbulent convective heat transfer from rough surfaces with two dimensional rectangular ribs. International Journal of Heat and Mass Transfer 20, 582–620.

[40] Meyer, L., 1982.Thermohydraulic characteristics of single rods with three dimensional roughness. International Journal of Heat and Mass Transfer 25, 1043–1058.

[41] Wilkie, D., 1966. Forced convection heat transfer from surfaces roughened by transverse ribs. In: Proceedings of the 2nd International Heat Transfer Conference, Vol. 1, and AICHE New York.

[42] Sheriff, N., Gumley, P., 1966.Heat transfer and friction properties of surfaces with discrete roughness. International Journal of Heat and Mass Transfer 9, 1297–1320.

[43] Gomelauri, V, 1964. Influence of two-dimensional artificial roughness on convective heat transfer. International Journal of Heat and Mass Transfer 7, 653–663.

[44] Wilkie, D., Mantle, P.L., 1979. Multi-start helically ribbed fuel pins for CAGR. Nuclear Energy 18, 277–282.

[45] Vilemas, J.V., Simonis, V.M., 1985. Heat transfer and friction of rough ducts carrying gas flow with variable physical properties. International Journal of Heat and Mass Transfer 28, 59–68.

[46] ASHRAE Standard 93-97, Method of Testing to Determine the Thermal Performance of Solar Collector, 1977.

[47] Prasad, B.N. and Saini, J.S., (1991).Optimal thermo-hydraulic performance of artificial roughness solar air heater, Solar Energy, 47, pp 91 – 96.

[48] Prasad, B.N., Saini J.S., “Effect of artificial roughness on heat transfer and friction factor in a solar air heater”, Sol Energy, 41(6), 555-560, 1988.

[49] Gupta D., Solanki S.C., Saini J.S., “Heat and fluid flow in rectangular solar air heater ducts having transverse rib roughness on absorber plates”, Solar Energy 51, 31-37, 1993.

[50] Sahu M.M., Bhagoria J.L., “Augmentation of heat transfer coefficient by using 90o broken transverse ribs on absorber plate of solar air heater”, Renewable Energy, 30, 2057-2063, 2005.

[51] Aharwal K.R., Gandhi B.K., Saini J.S., “Experimental investigation on heat-transfer enhancement due to a gap in an inclined continuous rib arrangement in a rectangular duct of solar air heater”, Renew Energy, 33, 585-596, 2008.

[52] Varun, Saini R.P., Singal S.K., “Investigation of thermal performance of solar air heater having roughness elements as a combination of inclined and transverse ribs on the absorber plate”, Renew Energy, 33, 1398-1405, 2008.

[53] Jaurker A.R., Saini J.S., Gandhi B.K., “Heat transfer and friction characteristics of rectangular solar air heater duct using rib-grooved artificial roughness”, Solar Energy, 80 (8), 895-907, 2006.

[54] Karwa R., Solanki S.C., Saini J.S., “Heat transfer coefficient and friction factor correlations for the transitional flow regime in rib-roughened rectangular ducts”, Int J Heat Mass Transf, 42, 1597-1615, 1999.

[55] Momin A.M.E., Saini J.S., Solanki S.C., “Heat transfer and friction in solar air heater duct with V-shaped rib roughness on absorber plate”, Int J Heat Mass Transfer, 45, 3383-3396, 2002.

[56] Muluwork, K.B., Saini, J.S., Solanki, S.C., 1998. Studies on discrete RIB roughened solar air heaters. In: Proceedings of National Solar Energy Convention, Roorkee; pp. 75–84.

[57] Karwa R., “Experimental studies of augmented heat transfer and friction in asymmetrically heated rectangular ducts with ribs on the heated wall in transverse, inclined, v-continuous and v-discrete pattern”, Int Conf Heat Mass Transfer, 30(2), 241-250, 2003.

[58] Hans V.S., Saini R.P., Saini J.S., “Heat transfer and friction factor correlations for a solar air heater duct roughened artificially with multiple v-ribs”, Solar Energy, 84, 898-911, (2010).

[59] Kumar A., Bhagoria J.L., Sarviya R.M., “Heat transfer enhancement in channel of solar air collector by using discrete w-shaped artificial roughened absorber”, in 19th National & 8th ISHMT-ASME Heat and Mass Transfer Conference, 2008.

[60] Lanjewar A.M. Bhagoria J.L., Sarviya R.M. Indian Journal of science and Technology 2010; Vol. 3 No.8 pp. 908-910.

[61] Saini S.K., Saini R.P., “Development of correlations for Nusselt number and friction factor for solar air heater with roughened duct having arc-shaped wire as artificial roughness”, Sol Energy, 82,1118-1130, 2008.

[62] Bhagoria J.L., Saini J.S., Solanki S.C., “Heat transfer coefficient and friction factor correlations for rectangular solar air heater duct having transverse wedge shaped rib roughness on the absorber plate”, Renew Energy, 25, 341-369, 2002.

[63] Saini R.P., Verma J., “Heat transfer and friction factor correlations for a duct having dimple-shape artificial roughness for solar air heaters”, Energy, 33, 1277-1287, 2008.

[64] Layek A., Saini J.S., Solanki S.C., “Effect of chamfering on heat transfer and friction characteristics of solar air heater having absorber plate roughened with compound turbulators”, Renewable Energy, 34, 1292-1298, 2009.

[65] Saini R.P., Saini J.S., “Heat transfer and friction factor correlations for artificially roughened ducts with expended metal mesh as roughness element”, Int J Heat Mass Transfer, 40(4), 973-986, 1997.

[66] Karmare S.V., Tikekar A.N., “Heat transfer and friction factor correlation for artificially roughened duct with metal grit ribs”, Int. Journal Heat Mass Transfer, 50, 4342-4351, 2007.

[67] Bopche SB, Tandale MS, Experimental Investigation on Heat Transfer and Friction Characteristics of a turbulators Roughened Solar Air Heater Duct, Int. Journal of Heat and Mass Transfer, Vol.52,pp.2834-2848,2009.