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Enhancement of Heat Transfer Using Artificial Roughness In Solar Air Heater

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ABSTRACT: *Heat transfer plays an important role in the field of thermal engineering. Heat transfer involves transfer of heat energy without transfer of mass and plays most important role in the field of power plant, refrigeration and air conditioning, electric transformer, and electronic equipment etc., Heat transfer takes place by three modes i.e. Conduction, convection and radiation. Conduction and convection mode need the working medium for heat transfer whereas radiation mode of heat transfer takes placeamong space bodies with or without medium. The convection mode of heat transfer is mostly used in industrial field where liquid; gases and air are the heat transfer medium is used. It is found that the convective heat transfer coefficient between hot gas to metal or hot metal to air is low. Due to the low value of heat transfer coefficient, the performance of the heat transfer system which is working with air as a working fluid is low. A lot of passive and active techniques are investigated to increase the efficiency or the heat transfer performance of system. Artificial roughness is the most important technique for enhancing the heat transfer among heat transfer techniques. Artificial roughness is defined by non-dimensional parameters as relative roughness pitch, relative roughness height and relative modifications for easy of analysis of system, comprising and evaluating of systems. A lot of research work is found in the field of enhancement of heat transfer by application of artificial roughness in the form of ribs as listed in details. This paper covers the introduction of artificial roughness in the field of heat transfer in various shapes and modifications made by researchers. This paper covers the literature of roughened heat transfer system by different types of artificial roughness, their technique/ correlations to evaluate the heat transfer rate, and analyse the results, which are very helpful in the field of heat transfer engineering, to selection of roughness, to predict the performance of system and compare the systems. This paper conclude that artificial roughness in the form of different typed of ribs used in heat transferring system, increase heat transfer rate around 2 to 4 times as compares to conventional type system.*

KEYWORDS: -*Heat Transfer, Artificial Roughness, passive and active techniques, relative roughness pitch, relative roughness height.*

I. INTRODUCTION

Energy plays an important role in the development processes ofthe world. There are two types of energy resources one is alternative source of energy and other is fossil fuel sources. Since the rapid depilation of fossil Fuel resources forces the investigator to search new resources of energy. Solar energy is the ultimate source of energy which has most promising, large quantity in nature, available free of cost and pollution free in nature, available at anywhere. Solar energy is collected by solar collector's i.e. solar air heater, solar water heater and photo voltaic methods. As the geographical location of India nature gives most efficient solar radiation over the country. India has agricultural environment and its economy depends on agriculture and industrial field. In view of Indian economically viability, solar air heater is the most economical solar collecting device in the field of crop drying, seasoning of wood, solar drier and maintaining the moderate temperature at industrial processes in winter season. Solar air heater is simple in design, easy of manufacturing and simple to use. Literature shows that heat transfer rate between the air and metallic plate is low, which leads to lower efficiency of the solar air heaters. Literature shows one of the most viable techniques of increasing the heat transfer rate and thermal efficiency of solar air heater is the application of artificial roughness in the form of ribs as shown in figure 1.This paper introducing the artificial roughness to enhance the heat transfer rate and mythology adopted by various investigators to achieve its goal.

II.ROUGHNESS GEOMETRIES IN HEAT TRANSFER FIELD

The roughness element may be

[1] Sand grain on heat transfer surface
[2] Two-dimensional ribs
[3] Three dimensional
[4] Grooves
[5] Compounding ribs
[6] Combination of rib and groove rib
[7] Transvers or
[8] Inclined.
[9] Wire fixation;
[10] Expanded wire mesh fixation;
[11] Rib formation by machining process;
[12] Dimple/ protrusion formation and
[13] Inverted u-shaped turbulators.
[14] Z-shaped rib

III. ROUGHNESSAND DUCT PERAMETERS

Artificial roughness is defined by non-dimensional parameters such as

[1] Relative roughness pitch (p/e)
[2] Relative roughness height (e/D)
[3] Angle of attack (α)
[4] Modified shape

Relative roughness pitch (p/e): It the ratio of distance between two consecutive ribs and height of the rib.
Relative roughness height (e/D): It is the ratio of rib height to equivalent diameter of the air passage.
Angle of attack (α): Angle of attack is defined as the inclination of rib with direction of air flow in the duct.
Aspect ratio: Aspect ratio is defined as the ratio of duct width to duct height. This factor also plays a very crucial role in investigating thermo-hydraulic performance.
Shape of roughness element: The common shape of roughness element is Square, circular, semi-circular, chamfered, arc shaped wire, dimple or cavity, compound rib-grooved, and v-shaped continuous or broken ribs with or without gap.

IV. EFFECT OF ROUGHNESS PERAMETERS ON HEAT TRANSFER

4.1 Relative Roughness Pitch (P/e)

roughness pitch is one of the most important key parameter of designing the artificial roughness in the field of heat transfer. Prasad and saini [1988] conducted an experimental investigation in solar air heater with artificial roughness plates with different Relative roughness pitches. They show very important phenomena of flow pattern downstreamof a rib as a function of relative roughness pitch as shown in Fig-1.They observed that the maximum heat transfer coefficient occurs in vicinity of the reattachment point due to the phenomenon of separation and reattachment of flow.The position of relative roughness pitch (p/e) for maximum heat transfer coefficient are listed shown in table.1

Table 1: relative roughness pitch (p/e) for maximum heat transfer rate.

S.NO.	Investigators	Roughness geometry	Value of (p/e) for maximum heat transfer
1.	Prasad and saini [1988]	Small dia. protrusion wires	10.00
2.	Bhagoria et al [2002]	Wedge shape rib	07.57
3.	Karwa et al [2001]	Chamfered rib	07.09
4.	Jaurker et al [2006]	Rib-grooved	06.00
5.	Sahu and bhagoria [2005]	90^0 broken transverse rib	13.33
6.	Karmare [2007]	Metal grit rib	17.50
7.	Saini and verma [2008]	Dimple shaped rib	10.00
8.	Varun et al [2008]	Combination ribs	08.00

4.2 Relative roughness height (e/D)

Relative roughness height is one of the most important key parameter of designing the artificial roughness in the field of heat transfer. Prasad and saini [1988] conducted an experimental investigation in solar air heater with artificial roughness plates with different Relative roughness height. They shows very important phenomena of flow pattern downstream of a rib as a function of relative roughness height as shown in Fig-2.They found that the flow pattern downstream and effect on the heat transfer and laminar sub layer as the rib height is changed. Heat transfer rate can be increased by creating local wall turbulence. Taking the rib height is slightly higher than the transition sub layer thickness can be obtained optimum thermo-hydraulic performance conditions. The trend for of relative roughness height (e/D) is listed for maximum heat transfer rate in Table. 2

Table 2: Trend of relative roughness height (e/D) for maximum heat transfer rate

S.NO.	Investigators	Roughness geometry	Value of (e/D) for maximum heat transfer
1	Prasad and saini [1988]	Small diameter protrusion wires	0.033
2	Bhagoria et al [2002]	Wedge shape rib	0.033
3	Karwa et al [2001]	Chamfered rib	0.0441
4	Jaurker et al [2006]	Rib-grooved	0.036
5	Karmare and tikekar [2007]	Metal grit rib	0.044
6	Saini and verma [2008]	Dimple shaped rib	0.0379
7	Momin et al [2002]	V-shaped rib	0.034
8	Layek et al [2007]	chamfered rib& grooved	0.04
9	Saini and saini [2008]	Arc shaped rib	0.0422

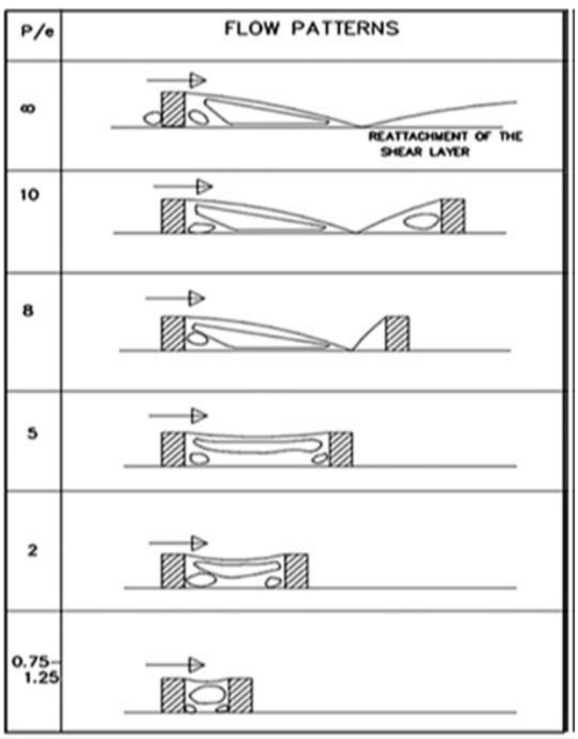


Fig. 1. Effect of rib pitch on flow [01].

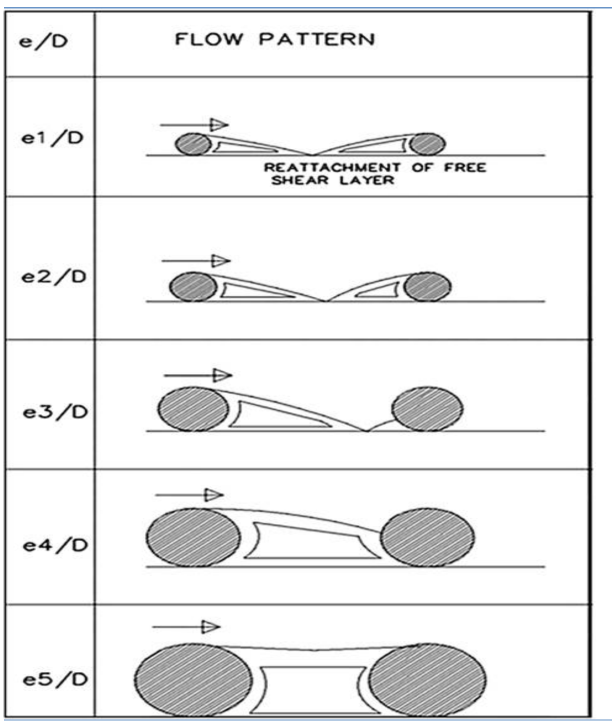


Fig. 2. Effect of rib height on flow [01].

4.3 Angle of attack (α)

Beside of the relative roughness pitch and relative roughness height, it has been experimentally found by various researchers that, the inclined rib gives higher heat transfer rate than the transverse rib because of the secondary flow induced by the rib, in addition to break the viscous sub layer and produces local wall turbulence. In other word the vertices move along the rib so subsequently to join the main stream causing the fluid to enter near the leading end of the inclined rib. These moving vertices therefore bring in cooler channel fluid in contact with leading end, raising the heat transfer rate. While the trailing end heat transfer is relatively lower. This phenomenon gives the strong span wise variation of heat transfer.

Table 2: Trend of Angle of attack (α) for maximum heat transfer rate

S.NO.	Investigators	Roughness geometry	Angle of attack (α) for maximum heat transfer
1	**Gupta et al. [1997]**	Inclined rib	70^o.
2	**Karwa et al.[2003]**	inclined rectangular ribs	60^0
3	**Kumar et al. [2008]**	discrete w-shaped ribs	45^o
4	**Lau et al. [1991]**	V-shape rib	60^o
5	**Kumar et al. [2011]**	Discrete inclined discrete rib	60^o
6	**Sukhmeet singh et al[2011]**	periodic discrete v-down rib	60^o
7	**Pongjet promvonge[2010]**	multiple V- baffle turbulator	60^0

V. REVIEW OF ROUGHNESS GEOMETRIES

The general arrangement of different types of roughness geometries reported by the various Investigators as follows.

[1] Wire fixation;
[2] Expanded wire mesh fixation;
[3] Rib formation by machining process;
[4] Dimple/ protrusion formation;
[5] Inverted u-shaped turbulators; and
[6] Z-shaped rib.

Wire fixation : Heat transfer enhancement and friction loss by fixing wire of different shapes, size and orientation by various investigators as an artificial roughness element on the absorber plate has been discussed below.

Transverse continuous rib : Prasad and saini [01] [1988] Investigated experimentally, the effect of relative roughness pitch (p/e) and relative roughness height (e/D) on the heat transfer coefficient and friction factor of the fully developed turbulent flow in a solar air heater duct with small diameter protrusion wire on absorber plate. The type and orientation of the geometry is depicted in fig.-5. It observed thatthe average Nusselt number and average friction factor in the roughened duct were as 2.10, 2.24, 2.38 and 3.08, 3.67, 4.25 times that of smooth duct for relative roughness height (e/D) of 0.020, 0.027 and 0.033 respectively. It has also been found that increase in the average Nusselt number and average friction factor in the roughened duct were about 2.38, 2.14, 2.01 and 4.25, 3.39, 2.93 times of that of the smooth duct for a relative roughness pitch (p/e) of 10, 15 and 20 respectively. The maximum enhancement heat transfer coefficient and friction factor were as 2.38 and 4.25 times than that of smooth duct respectively.

Transvers broken ribs : Sahu and bhagoria [02] [2005] Reported the effect on heat transfer coefficient and thermal Efficiency of solar air heater by providing 90^0 broken transvers rib on absorber plate. Integral rib Roughened absorber plate were prepared by fixing wire of 1.5mm diameter over one side of absorber plate as depicted in fig.-6, with the roughness geometry having pitch (p) range from 10-30mm, height of rib of 1.5mm, duct aspect ratio was 8 and Reynolds number of 3000-12000. It was also reported that, heat transfer coefficient and maximum thermal efficiency obtained as 1.25 to 1.4 times and 83.5% than that of smooth duct respectively. The maximum enhancement of heat transfer coefficient occurs at pitch of about 20mm. while on other side of this pitch, the Nusselt Number decreases.

Varun et al [03] [2008] Experimentally investigated the thermal preformation of solar air heater having roughness element as combination of inclined as well as transverse rib as depicted in Fig.-7, with the Reynolds number (Re) ranges from 2000-14000,relative roughness pitch (p/e) of 3-8 and relative roughness height (e/D) of 0.030. It was observed that the optimum thermal performance occurs having the value of relative roughness pitch (p/e) of 8.

Inclined ribs

Kumar et al. [04][2011]experimental study has been carried out for enhancement of heat transfer coefficient of a solar air heater having roughened air duct provided with artificial roughness in the form 60^o Discrete inclined rib. Considerably enhancement in heat transfer coefficient has been achieved with such roughness element. The investigated geometry has been shown in Fig.-8.

Aharwal et al[05] [2008] Investigated the effect of artificial roughness by inclined split rib arrangement in a rectangular duct in solar air heater depicted in fig.-9, considering the gap of width ratio (g/e) and gap of position ratio (d/w). The increase in Nusselt number and the friction factor were in the range of 1.48-2.59 times and 2.26-2.9 times of smooth duct, respectively.

Gupta et al. [06] [1997]carried out an extensive experimental investigation on fluid flow and heat transfer characteristics of artificially roughened solar air heater ducts with inclined wires as shown in Fig.-10. They found that maximum heat transfer coefficient occurred for an angle of attack of 60_ whereas the friction factor maximum for an angle of attack of 70^o.

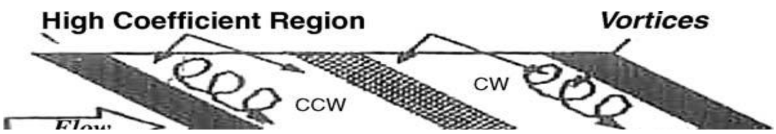


Fig. 3: Phenomena of Inclined rib

V- shape ribs

Momin et al [07] [2002] Experimentally investigated the effect of relative roughness height and angle of attack for fixed relative roughness pitch of 10 with the Reynolds number range of 2500- 18000 for a v-shaped rib as shown in fig.-11. It was found that the rate of increase of the Nusselt number with an increase in Reynolds number is lower than the rate of increase of the friction factor. It was also found that for the relative roughness height of 0.034, the v- shaped rib enhanced the value of Nusselt number by 1.14 and 2.30 times over inclined ribs and smooth plate.

Singh et al. [08] [2011] Experimental investigation on heat transfer and friction in rectangular ducts roughened with a new configuration of discrete v-rib on one broad wall are presented. The maximum enhancement in Nusselt number and friction factor has been obtained at relative gap position of 0.65 and is of order of 2.8 and3.0 times of that of the smooth duct, respectively. The investigated geometry has been shown in Fig.-12.

Karwa [09] [2003] Investigated the effect on heat transfer and friction factor by using the Transverse, inclined, v-continuous and v-discrete rib on absorber plate in solar air heater depicted in Fig.-13, with Reynolds number range of 2800-15000, relative roughness height (e/D) range of 0.0467 - 0.050 duct aspect ratio range of 7.19-7.75 at the fixed value of relative roughness pitch (p/e) of 10 and also developed the correlation for Stanton number and friction factor. The rib in the v-pattern were tested for both pointing upstream (V-up) and (V-down) to the flow. Enhancement in Stanton number and friction factor over that of the smooth duct was observed of the order of 65 -90% and 2.68 - 2.94 times, respectively. It is observed that 60^0 inclined rectangular ribs produces better results than transvers rib. The enhancement in the Stanton number over the smooth duct was up to 137%, 147%, 134% and 142% for the V-up continuous, V-down continuous, V-up discrete and V-down discrete rib arrangement respectively. The friction factor ratio for these arrangements was up to 3.92, 3.65, 2.47 and 2.58 respectively. Based on the equal pumping power, V-down discrete roughness provides the best heat transfer performance.

Lau et al. [10][1991] studied the effect of V-shaped ribs arrays on turbulent heat transfer and friction of fully developed flow in a square channel.Fig.14,represents the typical rib configurations. They showed that the 60^{O}V-shaped ribs have highest thermal performance.

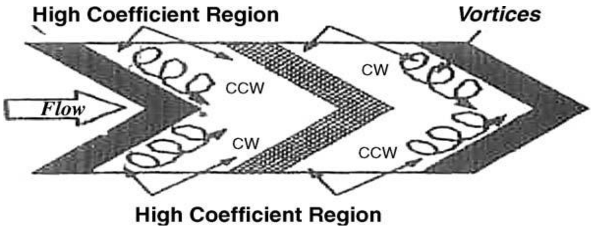


Fig. 4: Phenomena of V shaped rib

Arc shaped ribs : Saini and saini [11][2008] Experimentally investigated the effect on heat transfer coefficient and friction factor of relative roughness height (e/D) and angle of attack (α/90) with providing the arc shaped parallel wire on the absorber plate in solar air heater as depicted in fig.-15, with Reynolds number (Re) ranges of 2000-17000, relative roughness height (e/D) of 0.0213-0.0422and angle of attack (α/90) of 0.3333-0.6666 for a fixed relative roughness pitch (p/e) of 10. The maximum enhancement in Nusselt number was obtained as 3.80 times corresponding to the relative angle of attack (α/90) of 0.3333 at relative roughness height (e/D) of 0.0422. However, increment in the friction factor corresponding to these parameters was found to be only 1.75 times.

W-shaped rib : Kumar et al. [12] [2008] carried out an experimental investigation to determine the heat transfer distributions in solar air heater having its absorber plate roughened with discrete w-shaped ribs. The experiment encompassed Reynolds number (Re) range from3000 to 15,000, rib height (e) values of 0.75 mm and 1 mm, relative roughness height (e/D) 0.0168 and 0.0225 and relative roughness pitch (p/e) of 10 and angle of attack (a) 45^{o}. Thermal performance of roughened solar air collector was compared with that of smooth one under similar flow conditions and it was reported that thermal performance of the roughened channelwas1.2–1.8 times the smooth channel for range of parameters investigated. Discretization was found to have significant effect on heat transfer enhancement. The geometry investigated has been shown in Fig.-16.

Expanded Wire Mesh Fixation : Saini and saini [13] [1997] Experimentally investigated the effect on heat transfer coefficient and friction factor by providing the expanded metal mesh geometry on the absorber plate in solar air heater as depicted in fig.-17. For fully developed turbulent flow in a rectangular duct with a large aspect ratio of 11.1 has been found maximum Nusselt number and friction factor corresponding to relative long way length of mesh and relative short way length of mesh was 46.87, 71.87 and 25, 15 respectively. The maximum enhancement in Nusselt number and friction factor values were reported of the order of 4 and 5 times to that of the smooth absorber plate respectively.

Machining Ribs Of Different Shapes : The study of heat transfer and friction factor characteristics of solar air heater, experimentally investigated by various researchers using integral ribs generated on absorber plate by machining process reported in literature is discussed in following subsections.

Wedge shaped ribs : Bhagoria [14] [2002] Experimentally investigated the effect of relative roughness pitch (p/e) relative roughness height (e/D) and wedge angle on heat transfer coefficient and friction factor in solar air heater rectangular duct roughened with wedge shaped transvers integral rib depicted in fig.-18, taking the range of relative roughness pitch (p/e) of $60.17\phi^{-1.0264}$<p/e<12.12, range of relative roughness height (e/D) of 0.015-

0.033, Reynolds number (Re) range of 3000-18000 and wedge angle (ϕ) was 8-15^0. It has been observed that the maximum heat transfer occurs for a relative roughness pitch of about 7.57. While the friction factor decreased as the relative roughness pitch increased. The maximum enhancement of heat transfer at wedge angle of about 10^0. Author reported an enhancement in Nusselt number up to 2.4 times while the fiction factor increases up to 5.3 times as compared to smooth duct.

Chamfered ribs : Karwa et al [15] [1999] Experimentally investigated the effect ofrepeated integral chamfered rib roughness on absorber plate as depicted in fig.-19, with rib chamfered angle of -15^0 to 18^0 having aspect ratio of 4.8 to 12, relative roughness pitch (p/e) of 4.5 to 8.5, relative roughness height (e/D) of 0.0141 to 0.0328 and Reynolds number (Re) of 3000 to 20000. The highest heat transfer and friction factor was found for 15^0 chamfered rib angles. The heat transfer increases with increasing of aspect ratio from 4.65 to9.66 and the roughness function deceases with the increases in aspect ratio from 4.65 to 7.75. As compared to smooth absorber plate there was an appreciable increment in the value of thermal efficiency about 10 to 40% with chamfered rib roughened absorber plate of solar air heater due to enhancement of Nusselt number in order of 50 to 120%. The enhancement in thermal efficiency, fiction factor and Nusselt number were found to be strong function of the relative roughness height (e/D). The greatest enhancement was found for air heater with the highest relative roughness height.

COMBINATION OF DIFFERENT INTEGRAL RIB ROUGHNESS ELEMENTS

Jaurker et al [16] [2006] Experimentally investigated the effect on heat transfer and friction factor or fluid flow characteristics of relative roughness pitch(p/e), relative roughness height(e/D) and relative groove position by providing rib-grooved artificial roughness on absorber plate in rectangular solar air heater duct as depicted in fig.-20, withReynolds number(Re) of 3000 to 21000, relative roughness height(e/D) of 0.0181 to0.0363,relative roughness pitch(p/e) of 4.5 to 10, and groove position to pitch ratio(g/p) of 0.3 to 0.7. It has been observed that the maximum heat transfer was obtained for a relative roughness pitch (p/e) of 6 and the optimum condition for heat transfer was found at a groove position of 0.4. It has also been observed that as compared to smooth duct, the pressure of rib grooved artificial roughness increase the Nusselt number up to 2.75 times, while the friction factor raised up to 3.61 times in the range of parameters investigated.

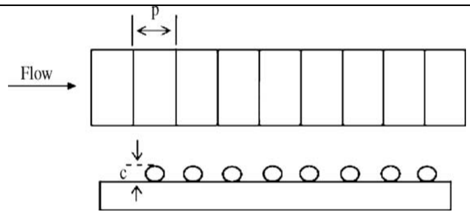
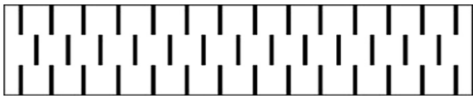
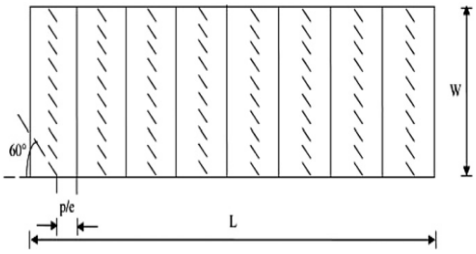
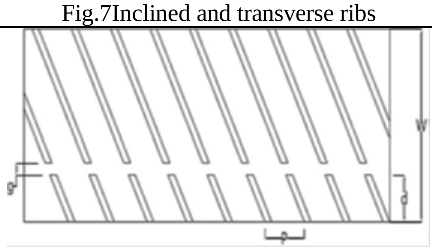
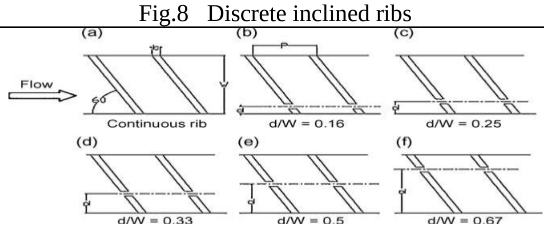
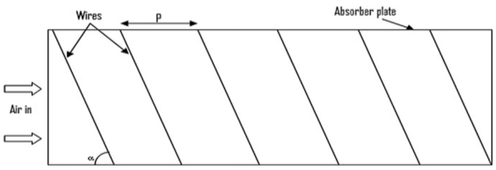
Layek et al [17] [2007] Reported the effect on heat transfer and friction factor characteristics with providing repeated integral transverse chamfered rib-groove roughness on absorber plate in solar air heater with Reynolds number (Re) of 3000 to 21000, relative roughness pitch (p/e) of 4.5 to 10, chamfered angle of 5 to30^0, relative groove position of 0.3 to 0.6 and relative roughness height (e/D) of 0.022, 0.04. It is found that Nusselt number and friction factor increased by 3.24 times and 3.78 times respectively as compared to smooth duct. Maximum enhancement of Nusselt number and friction factor was obtained corresponding to relative groove position of 0.4.

Dimple Shaped Geometry : Saini and verma et al [18] [2008] presented the effect of relative roughness pitch (p/e) and relative roughness height (e/D) of dimple shape roughness geometry on heat transfer and friction factor as depicted in fig.-21, by taking of Reynolds number (Re) of 2000 to 12000, relative roughness pitch (p/e) range of 8 to 12 and relative roughness height (e/D) range of 0.018 to0.037. It was found that Nusselt number and friction factor increases by 1.8 and 1.4 times respectively as compared to smooth duct.

Inverted U-Shaped Tabulators : Bopche and Tandale [19] [2009] Experimentally investigated the effect on heat transfer and friction factor by providing the inverted U-shaped turbulators on the absorber surface of a solar air heater duct. The inverted U-shaped tabulator shows appreciable heat transfer enhancement even at low value of Reynolds number (Re<5000) where rib were inefficient. The maximum enhancement in Nusselt number and friction factor at the Reynolds number of Re=3800 was the order of 2.388 and 2.50 times respectively. The maximum enhancement in the Nusselt number and friction factor values compared to the smooth duct were of the order of 2.82 and 3.72 times respectively. The 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.

Z-SHAPED GEOMETRY : Sriromrein and Promvong [20][2010]carried out an experimental investigation to study the heat transfer coefficient and friction factor of a rectangular duct roughened artificially with z-shape ribs. The roughness geometry is shown in Fig.-22. The 45_ Z-rib provides the highest increase in the heat transfer rate and the best thermal performance.

Table 3: Rib geometries:

S.NO.	INVESTIGATORS	Rib Geometries
1	**Prasad and saini [01] [1988]**	 Fig.5Transvers rib
2	**Sahu and bhagoria [02] [2005]**	 Fig.6Transverse broken ribs
3	**Varun et al [03] [2008]**	 Fig.7Inclined and transverse ribs
4	**Kumar et al. [04][2011]**	 Fig.8 Discrete inclined ribs
5	**Aharwal et al[05] [2008]**	 Fig.9 Inclined with gap rib
6	**Gupta et al. [06] [1997]**	 Fig.10Inclined rib

<table>
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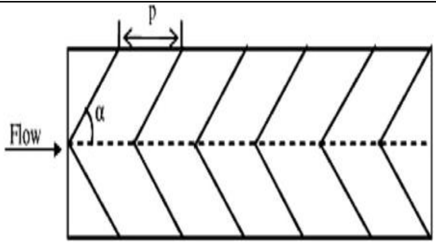


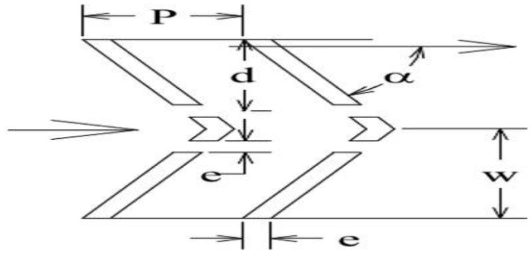
Fig.11V-Shaped Rib</td></tr>
<tr><td>8</td><td>Singh et al. [08] [2011]</td><td>


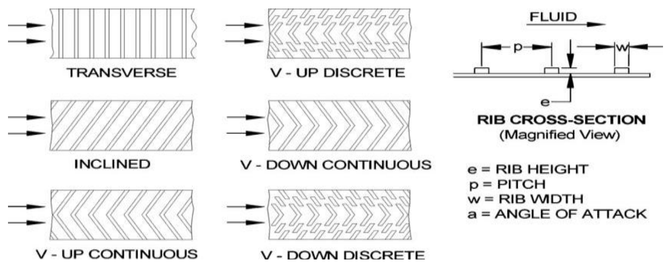
Fig. 12 Inverted -V -discrete rib</td></tr>
<tr><td>9</td><td>Karwa [09] [2003]</td><td>


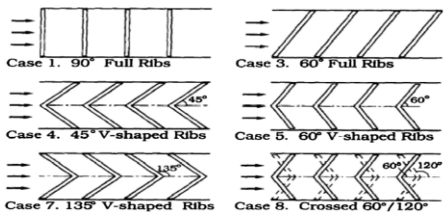
Fig.13   V-Continuous and Discrete</td></tr>
<tr><td>10</td><td>Lau et al. [10][1991]</td><td>


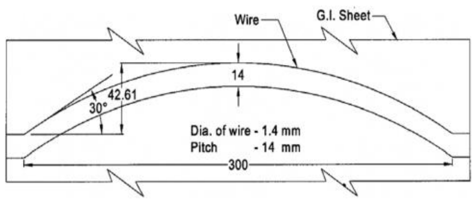
Fig.14   transvers and V-shaped ribs</td></tr>
<tr><td>11</td><td>Saini and saini [11][2008]</td><td>


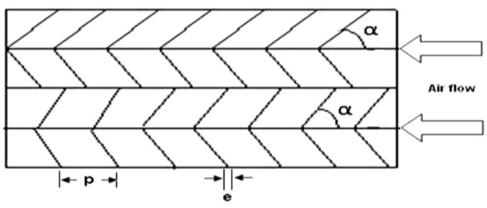
Fig.15Arc shaped ribs</td></tr>
<tr><td>12</td><td>Kumar et al. [12] [2008]</td><td>


Fig.16Discrete W-shaped ribs</td></tr>
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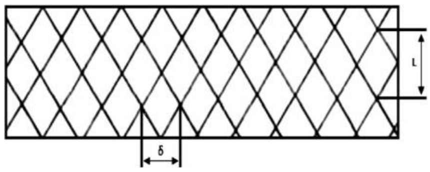
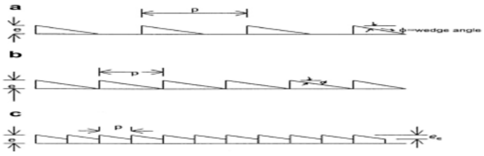
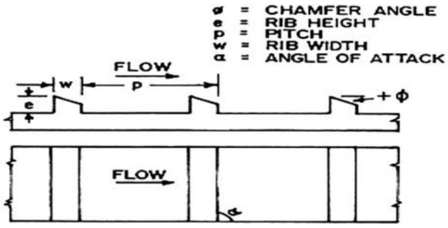
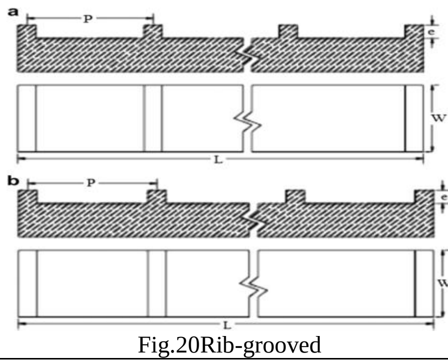
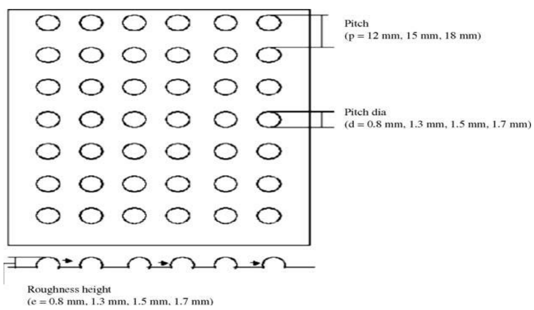
13	**Saini and saini [13] [1997]**	 Fig.17Expanded wire mesh fixation
14	**Bhagoria [14] [2002]**	 Fig.18Wedge shape rib
15	**Karwa et al [15] [1999]**	 Fig.19Chamfered rib geometry
16	**Jaurker et al [16] [2006]**	 Fig.20Rib-grooved
17	**Saini and verma et al [18] [2008]**	 Fig.21 Dimple shaped rib

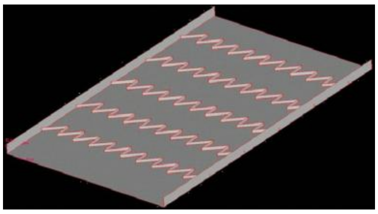
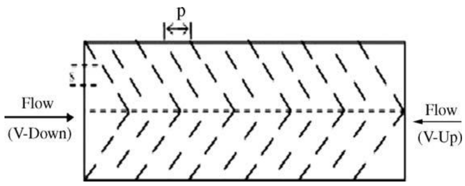
<table>
<tr><td>18</td><td>Sriromrein and Promvong [20][2010]</td><td>
Fig.22 Z-shaped rib</td></tr>
<tr><td>19</td><td>Muluwork et al.[21][2000]</td><td>

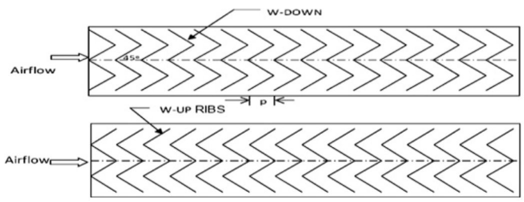
Fig.23 V-discrete rib</td></tr>
<tr><td>20</td><td>Atul lanjewar et al[22] [2011]</td><td>

Fig.24 W-shaped</td></tr>
</table>

Author	Roughness Geometries	Parameters	Heat transfer	Friction factor
Prasad and Saini	Transverse continuous ribs	(e/D):0.020-0.033 (p/e):10 Re:5000-50000	$St = \frac{f/2}{1+\sqrt{f}/2\{4.5(e+)^{0.28}\,Pr^{0.57}\,0.957(P/e)^{0.55}\}}$	$f = \frac{(W+2B)fs+Wfs}{2(W+B)}$ $fr = \frac{2}{[0.95(P/e)^{0.53}+2.5\ln\left(\frac{D}{2e}\right)-3.75]^2}$
Aharwal et al.	Inclined ribs with gap	(P/e):10-20 Re:5000-50000 (e/D):0.0377	$Nu = 0.002Re1.08\,(e/D)1.87$ $\times \exp[-0.45Ln(P/e)2](\alpha/60)0.006$ $\times \exp[-0.65Ln(\alpha/60)2](d/W)$ -0.32 $\times \exp[-0.12Ln(d/W)2](g/e)$ -0.03 $\times \exp[-0.18Ln(g/e)2](e/D)0.5$	$f = 0.071Re - 0.133(P/e)1.83$ $\times \exp[-0.44Ln(P/e)2](d/W)$ -0.43 $\times \exp[-0.14Ln(d/W)2](g/e)$ $-0.052 \times (\alpha/60)0.67$ $\times \exp[-0.12Ln(g/e)2](e/D)0.69$
Muluwork and Saini	Discrete V-shape ribs	g/e:0.5-2 d/w: 0.1667-0.667 W/H:5.84 α : 60^0 Re: 3000-18000 e/D:0.01-0.05	$Nu = 0.00534Re1.299(B/S)1.346(S'/S)1.112(e$ $/D)0.270(P'$ $/P)0.762\exp[-2.25(Ln(P'$ $/P)2)][-0.376LLn(1-\alpha/60)]$	$f = 0.7117Re^{-0.299}\left(\frac{B}{S}\right)^{0.636}(S'S)^{0.712}(D)^{0.113}(P'$ $/P)^{-0.0936}\exp[-1.26(Ln(1$ $-\alpha/70))^2]$
Verma and Prasad	Transverse continuous ribs	P'/P:0.2-0.8 S'/S:1.1-2.3 B/S:3-9 α : 60-90 Re:3032-17652 e/D:0.02-0.034	$Nu = 0.08596\left(\frac{P}{e}\right)^{-0.054}(e/D)^{0.0722}Re^{0.723}$ for e+ ≤24 $Nu = 0.02954\left(\frac{P}{e}\right)^{-0.016}(e/D)^{0.021}Re^{0.802}$ for e+ >24	$f = 0.245\left(\frac{P}{e}\right)^{-0.206}(e/D)^{0..243}Re^{-1.25}$

Gupta	Inclined continuous ribs	(P/e):10-40 Re: 5000-20000 (e/D): 0.020-0.05 α: 30⁰-90⁰	$Nu = 0.0024\left(\frac{e}{D}\right)^{0.001}(W/H)^{-0.06}Re^{1.084} \times \exp\left[-0.004\left(1-\frac{\alpha}{60}\right)^2\right] for e+ < 35$ $Nu = 0.0071\left(\frac{e}{D}\right)^{-0.24}(W/H)^{-0.028}Re^{0.88} \times \exp\left[-0.475\left(1-\frac{\alpha}{60}\right)^2\right] for e+ \geq 35$	$f = 0.1911\left(\frac{e}{D}\right)^{0.196}\left(\frac{W}{H}\right)^{-0.093}(Re)^{1.084} \times \exp[-0.993(1-\alpha/70)^2]$
Saini & Saini	Expanded Metal Mesh	(e/D): 0.012-0.039 (S/e):15062-42.87 (L/e):25-71.87 (Re):1900-13000	$Nu = 4.0 \times 10^{-4} \times Re^{1.22}\left(\frac{e}{D}\right)^{0.625}(S/e)^{2.22} \times \exp\left[-1.25\left\{Ln\left(\frac{S}{10e}\right)\right\}^2\right](L/e)^{2.26} \times \exp\left[-0.824\left\{Ln\left(\frac{L}{10e}\right)\right\}^2\right]$	$f = 0.815\ Re^{0.361}\left(\frac{L}{e}\right)^{0.266}\left(\frac{S}{10e}\right)^{-0.19}(10(e/D))^{0.591}$
Momin	V-shaped ribs	(e/d):0.01-0.03 (P/e):10-40 Re:2500-18000	$Nu = 0.067Re^{0.888}\left(\frac{e}{D}\right)^{0.424}(\alpha/60)^{-0.077}\exp\left[-0.782(Ln(\alpha/60))^2\right]$	$f = 6.266Re^{-0.425}\left(\frac{e}{D}\right)^{0.565}(\alpha/60)^{-0.093}\exp\left[-0.719 \times (Ln\,\alpha/60)^2\right]$
Karwa	Chamfered ribs	(W/H):4.8,6.1,7.8,9.66 and 12 (e/D):0.0141-0.0328 (P/e): 4.5,5.8,7 and 8.5 ɸ: 3000-20000	$g = 103.77e^{-0.006\phi}\left(\frac{W}{H}\right)^{0.5}(P/e)^{-2.56} \times \exp\left[0.7343\left\{Ln\left(\frac{P}{e}\right)\right\}^2\right](e+)^{-0.31}$ $g = 32.26\left(\frac{W}{H}\right)^{0.5}(P/e)^{-2.56} \times \exp\left[0.7433\left\{Ln\left(\frac{P}{e}\right)\right\}^2\right](e+)^{-0.08}$	$R = 1.66e^{-0.0078\phi}\left(\frac{W}{H}\right)^{-0.4}(P/e)^{2.695} \times \exp\left[-0.762\left\{Ln\left(\frac{P}{e}\right)\right\}^2\right](e+)^{-0.075}$ for 5≤ e+ <20 $R = 1.325e^{-0.0078\phi}\left(\frac{W}{H}\right)^{-0.4}(P/e)^{2.695} \times \exp\left[-0.762\left\{Ln\left(\frac{P}{e}\right)\right\}^2\right]$ for 20≤ e+ <60
Bhagoria et al.	Wedge Shaped rib	(e/d):0.015-0.033 (P/e):60.17 $\phi^{-1.0264}$<(P/e)<12.15. 2013 Re:3000-18000	$Nu = 1.89 \times 10^{-4}\ Re^{1.21}\left(\left(\frac{e}{d}\right)\right)^{0.426}(P/e)^{2.94} \times \exp\left[-0.71\left\{\ln\left(\frac{P}{e}\right)\right\}^2\left(\frac{\Phi}{10}\right)\right] \times exp[-1.5\{\ln(\Phi/10)\}]$	$f = 12.44Re^{-0.18}((e/d)^{0.99})((P/e)^{-0.52})((\Phi/10)^{0.49})$
Saini and Saini	Arc shaped ribs	(P/e):10 (e/d):0.021-0.042 Re:2000-17000 (α/90):0.33-0.66	$Nu = 0.001047Re^{1.3186}\left(\left(\frac{e}{d}\right)\right)^{0.3772} \times (\alpha/90)^{-0.1198}$	$f = 0.14408Re^{-0.17103}((e/d)^{0.1765})((\Phi/10)^{0.1185})$
Saini and Verma	Dimpled Surfaces	(P/e):8-10 (e/d):0.018-0.037 Re:2000-12000	$Nu = 5.2 \times 10^{-4}\ Re^{1.27}(P/e)^{3.15} \times \exp\left[-2.21\left\{\ln\left(\frac{P}{e}\right)\right\}^2\right](e/D)^{0.033} \times [\exp(-1.3)\{\ln(e/D)\}^2]$	$f = 0.642Re^{-0.423}\left(\frac{P}{e}\right)^{-0.465}\left[\exp(0.054)\left(\log\left(\frac{p}{e}\right)^2\right)\right] \times (e/D)^{-0.0214}[\exp(0.84)(\log(e/d)^2)]$
Karmare & tikekar	Arc shape ribs	(e/D):0.035-0.044 (P/e):12.5-36 (Re):4000-17000	$Nu = 2.4 \times 10^{-4}\ Re^{1.3} \times \left(\frac{e}{D}\right)^{0.42}\left(\frac{l}{s}\right)^{-0.146}(P/e)^{-0.27}$	$f = 15.55 \times Re^{-0.263} \times \left(\frac{e}{d}\right)^{0.91}\left(\frac{l}{s}\right)^{-0.27}(P/e)^{-0.51}$

VI. CONCLUSION

An attempt has been made in the present paper to report the heat transfer coefficient and friction factor characteristics of artificially roughened duct in solar air heater using of different shapes of geometry. It can be concluded that there is a considerable enhancement in heat transfer with little penalty of friction. This is interesting to see for further work that how Correlations can be developed for heat transfer and Friction factor for solar air heater ducts having artificial roughness of different geometries for different investigators. These correlations can be used to predict the thermal efficiency, effective efficiency and then hydraulic performance of artificial roughened solar air heater ducts. Correlations developed for heat transfer and friction factor of solar air heater duct having artificial roughness of different geometries by different investigators are also presented in tabular form. These correlations can be used to predict the thermal efficiency, effective efficiency and hydraulic performance of artificially roughened solar air heater duct. Information provided in the present paper may be useful to the beginners in this area of research to find out and optimize the new element geometries for the maximum enhancement of heat transfer.

Nomenclature

A_c	surface area of absorber plate, m2
B	half-length of full V-rib element, m
C_p	specific heat of air, J/kg K
D, Dh	equivalent or hydraulic diameter of duct, m
e	rib height, m
g	groove position, m
h	heat transfer coefficient, W/m2 K
H	depth of air duct, m
I	intensity of solar radiation, W/m2
K	thermal conductivity of air, W/m K
L	length of test section of duct or long way length of mesh, m
m	mass flow rate, kg/s
P	pitch, m
DP	pressure drop, Pa
q_u	useful heat flux, W/m2
Q_u	useful heat gain, W
Q_l	heat loss from collector, W
Q_t	heat loss from top of collector, W
S	length of discrete rib or short way length of mesh, m
T_o	fluid outlet temperature, K
T_i	fluid inlet temperature, K
T_a	ambient temperature, K
T_{pm}	mean plate temperature, K
W	width of duct, m

Dimensionless parameters

e/D, e/Dh	relative roughness height
e/H	rib to channel height ratio
f	friction factor
g/P	relative groove position
Nu	Nusselt number
N_{us}	Nusselt number for smooth channel
N_{ur}	Nusselt number for rough channel
p/e	relative roughness pitch
Pr	Prandtl number
Re	Reynolds number
St	Stanton number
W/H	duct aspect ratio

Greek symbols

ϕ	rib chamfer/wedge angle, degree
η_{th}	thermal efficiency
μ	dynamic viscosity, Ns/m^2
ρ	density of air, kg/m^3
α	angle of attack, degree

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