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A Review on Solar Air Heater using various roughness geometries on roughened duct to increase heat transfer coefficient and friction characteristics

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Abstract
Heat transfer coefficient between absorber surface of collector and fluid i.e. air can be improved by providing artificial roughness on the absorber surface. In this way the Thermal efficiency is increased. Due to roughness geometry pumping power of solar collector is increased due to friction losses in the duct. So, it is necessary to take into account size, shape and flow pattern of various roughness elements to increase maximum efficiency with minimum frictional losses. Various artificial roughness geometries have been reported in the literature by investigators, for determining the effect of various roughness geometries on heat transfer enhancement and friction characteristics in roughened duct of solar air heater. Reviews of various studies are presented in this study.

1. Introduction

Due to advancement in technology and fast growing population in each and every field such as Agriculture & Research, Industrial, energy is the main requirement and same trend will be increasing day by day. Conventional energy resources are depleting very fast. They are not sufficient to meet the energy demands very long. Hence the desire of mankind is to find alternate energy resources. Alternate energy resources can be divided into renewable and non-renewable energy resources. Although there are many forms of renewable energy resources available to us, solar energy is most promising source, due to clean energy, available freely, free of cost, pollution free, presence everywhere, non exhaustive nature. The easiest methodology for making proper use of solar energy is its conversion to thermal energy using solar collector. These solar collectors are part of solar water heater and solar air heater which are used for heating water and heating air respectively. Solar air heater has been used to deliver heated air at low to moderate temperatures which can be used for crop drying and industrial applications. The thermal efficiency of solar air heater having smooth plate collector is very low due to low convective heat transfer coefficient between absorber plate and the air flowing in the duct. In a smooth plate solar air heater a thin viscous sub layer develops next to the wall in turbulent boundary layers where the velocity is relatively low. In this region heat transfer is predominated by conduction and beyond this heat transfer process is dominated by convection. The objective is to increase heat transfer coefficient between the absorber plate and the air flowing over the plate. By providing roughness element on the absorber surface of plate can improve heat transfer coefficient, but it would result in increased frictional losses. Therefore greater power is required by blower. In order to keep the frictional losses at minimum level, the turbulence must be created only in the region very close to the duct surface i.e. in laminar sub-layer.

2. Performance Analysis of Conventional solar Air Heater

$$Q_u = A_c\left[I(\tau\alpha)_e - U_l(T_{pm} - T_{am})\right] \quad (1)$$

Where

$$\eta_{th} = \frac{Q_u}{A_c I} \quad (2)$$

$$Q_u = \dot{m}\, C_p (T_o - T_i) \quad (3)$$

$$Q_u = h\, A_c (T_{pm} - T_{am}) \quad (4)$$

Q_u	useful energy gain in the collector (W)
A_c	collector area (m^2)
I	insolation on tilted surface (W/m^2)
$(\tau\alpha)_e$	effective transmittance-absorptance product
T_{pm}	mean temperature of absorber plate (K)
T_{am}	ambient temperature (K)
U_l	overall heat loss coefficient (W/m^2K)

Hottel-Whillier-Bliss equation reported by Duffie and Beckman(1980) commonly used for predicting useful energy gain by the air flowing through the duct
Eq. (4) shows that useful energy gain in a solar air heater can be increased by increasing heat transfer coefficient between absorber plate and flowing air.

$$h = \frac{\dot{m} C_p (T_o - T_i)}{A_c\left(T_{pm} - T_{am}\right)} \quad (5)$$

2. Experimental Approach

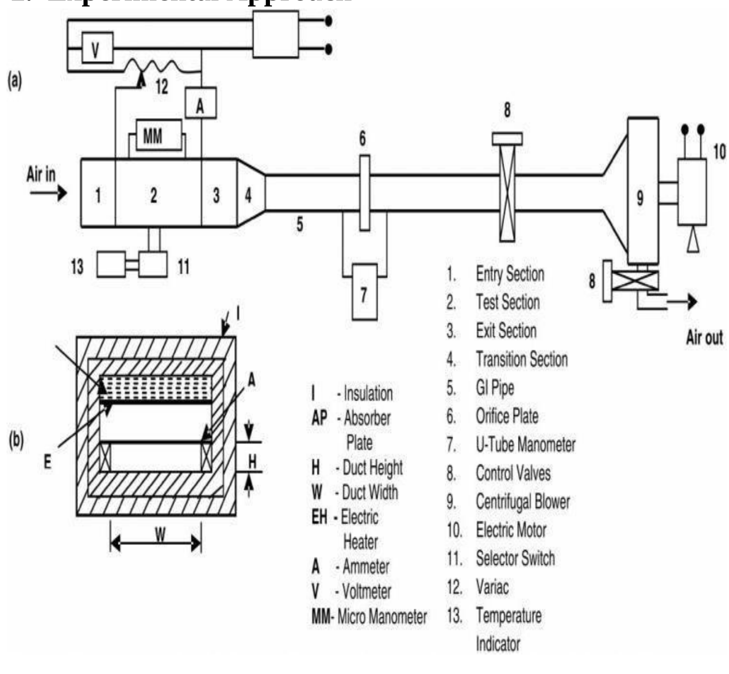

Fig.1: Schematic Diagram of Experimental Setup

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Experimental set up components and instruments have been checked for proper orientation. Inclined U-tube manometer and Micro manometer are properly leveled. Blower is switched on and the flow control valve is adjusted to give a predetermine rate of air flow to the test section. The test runs to collect friction and heat transfer data under steady state conditions. When a change in operating conditions is made, it takes about 30 to 35 minutes to reach such a steady state.

3. Literature and Findings

The concept of artificial roughness was first applied by Joule to enhance heat transfer coefficients for in tube condensation of steam and hence then many experiments were carried out on the application of artificial roughness in the areas of compact heat exchangers, electronic experiments, nuclear reactors. Gupta et al. (1993) carried out investigation on heat and fluid flow in rectangular solar air heater ducts having transverse rib roughness on absorber plate as shown in Fig. 2. The investigation covered a Reynolds number a range of 3000-18000 for a duct aspect ratio of 6.8-11.5, relative roughness height of 0.018-0.052 at a relative roughness pitch of 10. Correlations for friction factor and heat transfer were developed by author.

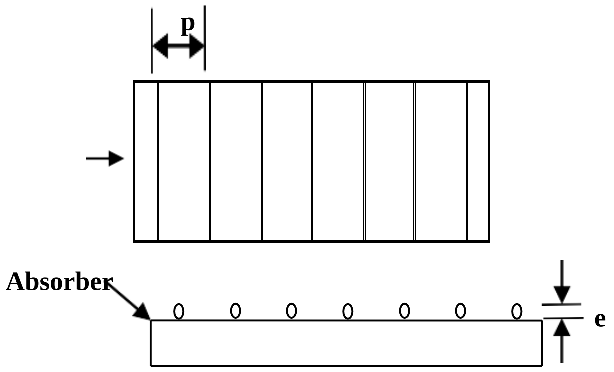

Fig. 2: Type of roughness geometry investigated by Gupta et. al (1993).

Saini and Saini (1996) carried out experimental investigation with expanded metal mesh as roughness element as shown in Fig. 3. The range of the system and operating parameters included L/e from 25 to 71.87, S/e from 15.62 to 46.87 & e/D 0.012 to 0.034 for Reynolds number 1900 to 13000. Correlations for Nusselt number and Friction factor have been developed in terms of relative longway length of mesh (L/e), relative shortway length of mesh (S/e) and relative height of mesh (e/D). It is seen that average Nusselt number increases with increase in relative longway length of mesh from 25 to 46.87, but for higher values Nusselt number decreases.

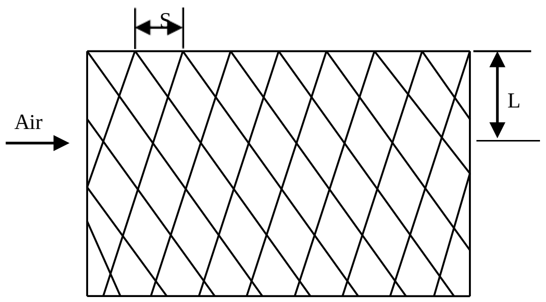

Fig. 3: Type of roughness geometry investigated by Saini & Saini (1996).

Karwa et al. (1999) experimentally studied the effect of relative roughness height, relative roughness pitch, rib head chamfer angle and duct aspect ratio on the friction factor and heat transfer coefficient with roughness geometry as shown in Fig. 4..Author investigated that presence of chamfered ribs on wall of duct increases Stanton number as well as friction factor. Highest heat transfer as well as highest friction factor exists for a chamfer angle of 15°.As aspect ratio increases from 4.65 to 9.66, heat transfer function also increases and then attains nearly a constant value.

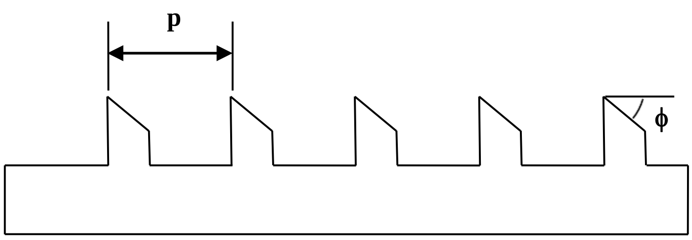

Fig. 4: Type of roughness geometry investigated by Karwa et. al (1999).

Momin et al. (2002) investigated the effect of geometrical parameters of V-shaped ribs on heat transfer and fluid flow characteristics of rectangular duct of solar air heater having V-shaped ribs on absorber plate as shown in Fig. 5..Author reported that for an angle of attack of 60° the maximum enhancement of Nusselt number and friction factor has been found to be respectively 2.30 and 2.83 times that of smooth duct. It was found that for relative roughness height of 0.034 and for angle of attack of 60°, the V-shaped ribs enhances the values of Nusselt number by 1.14 and 2.30 times over inclined ribs and smooth plate case at Reynolds number of 17034

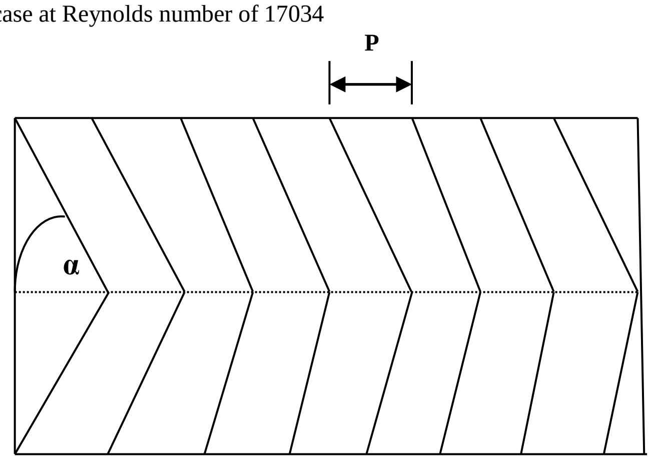

Fig. 5: Type of roughness geometry investigated by Momin et. al (2002).

Bhagoria et al. (2002) performed experiments to collect heat transfer and friction data with one wall of solar air heater rectangular duct roughened by wedge shaped transverse integral ribs as shown in Fig. 6.It is concluded that presence of ribs increases Nusselt number up to 2.4 times and friction factor rises up to 5.3 times for the range of parameters investigated. Maximum enhancement of heat transfer occurs at a wedge angle of about 10°, while friction factor increases as wedge angle increases. Statistical correlations for Nusselt number and friction factor have been developed as a function of rib spacing, rib height, rib wedge angle, and Reynolds number.

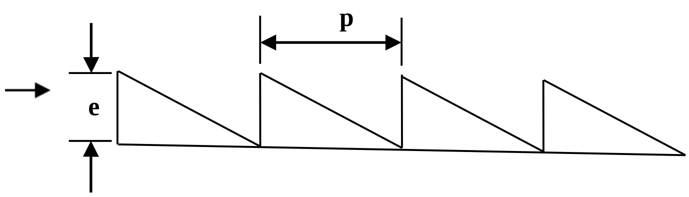

Fig. 6: Type of roughness geometry investigated by Bhagoria et. al (2002).

Layek et.al (2007) reported an experimental investigation on heat and fluid flow characteristics in solar air heater duct having repeated integral transverse chamfered rib-groove roughness as shown in Fig.

7.Investigation encompassed the Reynolds number range of 3000-21000,relative roughness pitch of 4.5-10,chamfer angle of 5°-30°,relative groove position of 0.3-0.6 and relative roughness height of 0.022-0.04.Author reported that Nusselt number and friction factor increase by 3.24 times and 3.78 times respectively as compared to smooth duct. The highest Nusselt number occurs for chamfer angle of 18° and maximum heat transfer enhancement occurs for the relative roughness pitch of 6 and relative groove position of 0.4.

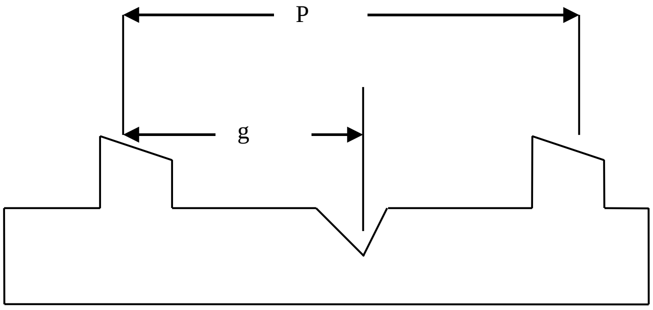

Fig. 7: Type of roughness geometry investigated by Layek et. al (2007)

Kumar and Saini (2008) reported CFD based analysis of solar air heater duct provided with artificial roughness in the form of thin circular wires in arc shaped geometry as shown in Fig. 8.The investigation covered the range of roughness parameters relative roughness height (e/D) from 0.0299 to 0.0426 and relative roughness angle (α/90) from 0.333 to0.0666 and Reynolds number (Re) from 6000 to 18000 for solar radiation of 1000 W/m^2 .The effect of relative roughness height and relative arc angle on Nusselt number and friction factor has been analyzed by the author. Nusselt number has been found to increase with increase in Reynolds number whereas friction factor decreases with increase in Reynolds number for all combination of relative roughness height (e/D) and relative arc angle (α/90).

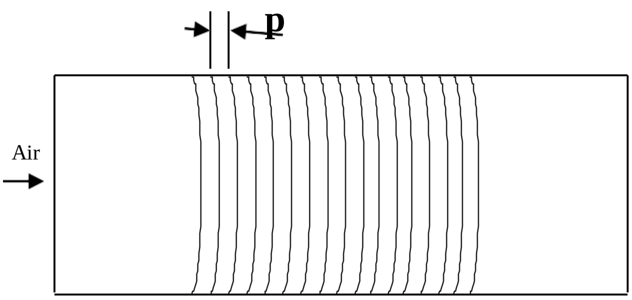

Fig. 8: Type of roughness geometry investigated by Kumar and Saini (2008).

Saini and Saini (2008) investigated experimentally the effect of relative roughness height(e/D) and relative angle of attack (α/90) of arc-shaped parallel wire on the heat transfer coefficient and friction factor as depicted in Fig.9. The maximum enhancement in the Nusselt number was obtained as 3.80times corresponding to the relative arc angle(α/90) of 0.3333 at relative roughness height of 0.0422.

Soi et. al (2010) reported CFD based investigation to study effect of roughness element pitch on heat transfer and friction characteristics .The geometry of the roughness element is shown in Fig. 10. The investigation covered a Reynolds number a range of 4000-16000, relative roughness pitch (p/e) from 7.5-10.7 for fixed relative roughness height (e/D) of 0.029. It was observed that roughened absorber plate enhances heat transfer coefficient at the cost of friction penalty. Author also developed Nusselt number and Friction factor correlations by using the data generated under CFD based investigation.

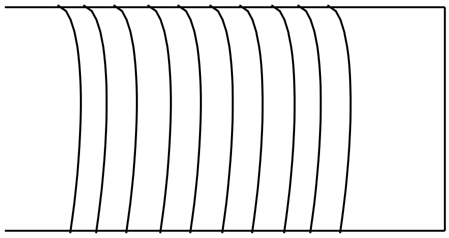

Fig. 9: Type and orientation of roughness geometry investigated by Saini and Saini (2008).

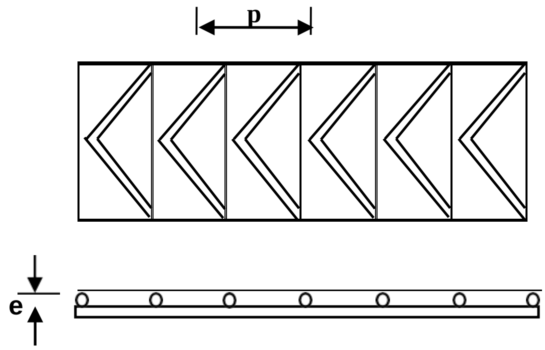

Fig. 10: Type of roughness geometry investigated by Soi et. al (2010).

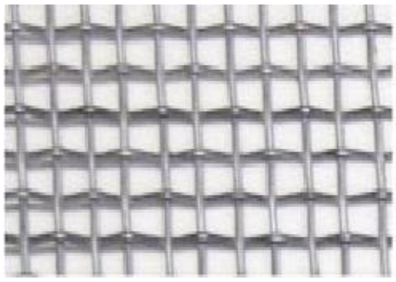

Fig. 11: Roughness geometry investigated by Mahajan et al. (2010)

Mahajan et al. (2010) performed an experimental investigation on heat transfer and friction for artificially roughened solar air heater duct roughened with plain woven square wire mesh as shown in Fig. 11.

Bhushan and Singh (2011) investigated solar air heater duct roughened with protrusions for the range of system and operating parameters. The shape and orientation of the roughness geometry is shown in Fig. 12. It was reported that an increase in heat transfer and friction loss for the duct having absorber plate roughened with investigated type of roughness geometry. Author also developed Nusselt number and Friction factor correlations for predicting performance of the system having investigated type of roughness geometry.

Sharma et al. (2011) reported CFD based investigation of solar air heater duct provided with artificial roughness in the form of square type protrusion shape geometry. Shape and orientation of roughness geometry investigated by author. The investigation covered a Reynolds number range of 4000-20000 and relative roughness pitch of 38.8-61.1 at fixed relative height of0.016 and it was observed that roughened absorber plate results into higher heat transfer coefficient than smooth plate.

Bhaskar et. al (2011) investigated the effect of long way length of roughness element on performance of artificially roughened solar air heater duct by using CFD software. The author used wire mesh as roughness geometry as shown in Fig. 13. and covered a Reynolds number a range of 6000-16000, relative short way length (S/e) 10-

23.33, relative long way length (L/e) 6.66-16.66 for relative roughness height of 3mm. Author predicts that for a range of Reynolds number, Nusselt number increases with an increase in relative long way length (L/e) an relative short way length (S/e) ; shows maxima and further it decreases with increase in the values

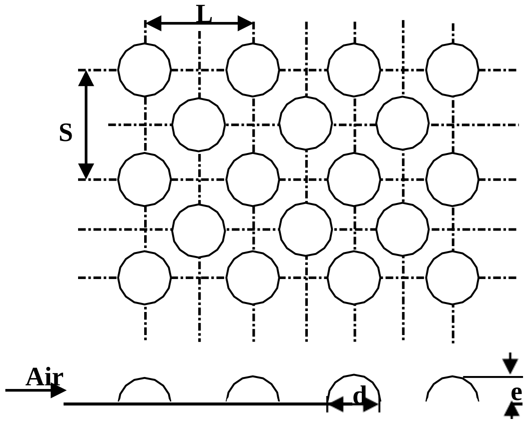

Fig. 12. Type of roughness geometry investigated by Bhushan & Singh (2011).

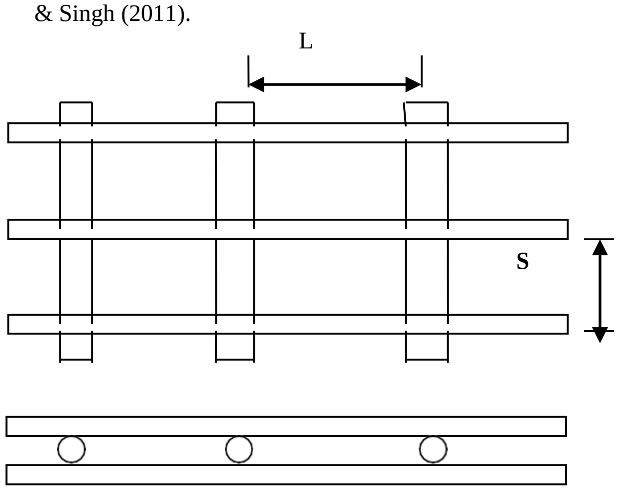

Fig. 13: Type of roughness geometry investigated by Bhaskar et. al (2011).

Kumar et al. (2013) investigated and developed correlations for Nusselt number and friction factor for solar air heater with roughened duct having multi v-shaped with gap rib as artificial roughness geometry as shown in Fig. 14. As compared to smooth duct the presence of multi v-shaped rib with artificial roughness yields Nusselt number up to 6.74 times while the friction factor rises up to 6.37 times in the range of parameters investigated.

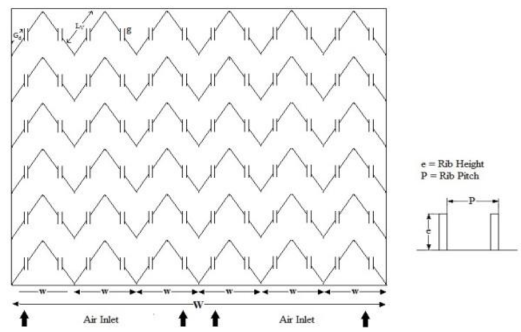

Fig. 14: Roughness geometry investigated by Kumar et al. (2013).

Singh J. et.al (2014) investigated longway and shortway thermo hydraulic performance of solar air heater. The author used triangular protrusion as roughness geometry as shown in Fig. 15. and covered a Reynolds number a range of 4000-20000, a relative longway length (L/e) 18.75-37.5, a relative shortway length (L/e) 18.75-37.5, for a relative roughness height of 0.03. Author predicts that for a range of Reynolds number, Nusselt number increases with an increase in relative long way length (L/e) an relative short way length (S/e) ; shows maxima and further it decreases with increase in the values.

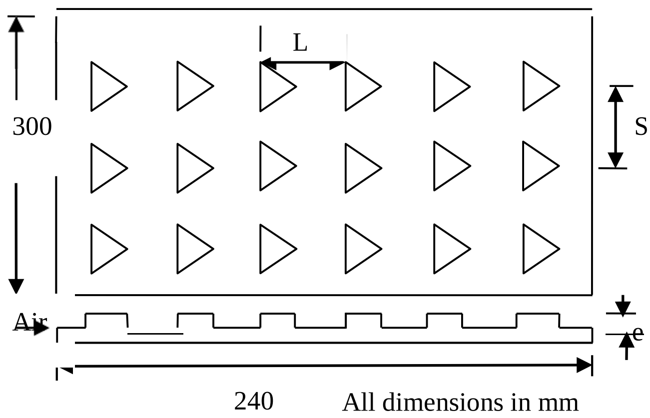

Fig.: 15: Type of roughness geometry investigated by Singh et al.(2014)

Table 1: Correlations developed for heat transfer and friction factor for different roughness geometries used in solar air heaters.

S.No	**Author**	**Roughness geomerties**	**Heat transfer**	**Frction factor**
1	Bhagoria et al.(1993)	Wedge shaped rib	$Nu = 4.0\times10^{-4}\times Re^{1.22} (e/D)^{0.625}(S/e)^{2.22}\times exp[-1.25\{In(S/10e\}^2\}] (L/e)^{2.26}\times exp\{-0.824[In (L/10e)^2]$	$f=0.815Re^{0.361} (L/e)^{0.226}(S/10E)^{0.19}(10e/D))^{0.591}$
2	Saini and Saini	Expanded metal mesh	$Nu = 4\times10^{x}Re^{1.22}(e/D)^{0.625}(S/e)^{2.22} \times exp[-1.25\{In(5/10e)\}^2](L/e)^{2.26} \times exp[-0.824\{In(L/10e)\}^2]$	$f = 0.815Re^{0.361}(l/e)^{0.266}(5/10e)^{-2.31}(10e/D)^{0.591}$
3	Momim	V-shaped ribs	$Nu=0.067Re^{0.88}(e/D)^{0.424}(a/60)^{-0.077} exp[-0.782In(a/60))^2]$	$f = -6.266Re^{-0.425}(e/D)^{0.565}(a/60)^{0.093} exp[0.719\times(In a/60)^2]$

4	Layek et al.(2007)	Chamfered rib-groove	$Nu = 0.00225(Re)^{0.92}(e/D)^{0.52}(P/e)^{1.72}(g/p)^{-1.21}(\phi)^{1.24}\times[\exp\{-0.22(\ln\phi)^2\}\times[\exp\{-0.46(\ln(p/e))^2\}]\times[\exp\{-0.74(\ln(g/p))^2]$	$f = 0.00245(Re)^{-0.124}(e/D)^{0.365}(P/e)^{4.32}(g/p)^{-1.24}\times[\exp(0.005\phi)]\times[\exp\{-1.09(\ln(p/e))^2\}]\times[\exp\{1.513(\ln(g/p)^2\}]$
5	Saini and Saini(2008)	Arc shaped wire roughness	$Nu = 0.00104(Re)^{1.3186}(e/D)^{0.3372}(\alpha/90)^{-0.1195}$	$f =0.001049Re)^{1.3186}(e/D)^{0.1765}(\alpha/90)^{0.1185}$
6	Varun et al.(2008)	Combination of inclined & transvers ribs	$Nu = 0.0006\ (Re)^{1.213}(P/e)^{0.0114}$	$f = 1.0858\ (Re)^{-0.3685}(P/e)^{0.114}$
7	Singh J et al.(2014)	Triangular shaped geometry	$Nu=2.74\times10^{-3}\times1.358\times10^{-19}(Re)^{1.2579}\times(L/e)^{-0.538}(S/e)^{13.362\exp}[-11.62\{\log(S/e)\}^2]$	$f = 0.052(Re)^{-0.57}(L/e)^{-1.2382}(S/e)^{-0.94}$

4. Conclusions

Use of artificially roughened surfaces with different types of roughness geometries is found to be most effective technique to enhance heat transfer rate from heated surface to flowing fluid at cost of moderate rise in fluid friction.

Use of protrusions on absorber plate is an effective technique to increase heat transfer rate, less expensive and cost no extra weight on absorber plate. An increse in Nusselt number and friction factor is noticed by several researchers with the use of artificial roughness element. Hence, use of artificial roughness elements desireable.

Correlations developed for heat transfer and friction factor for solar air heater ducts having artificial roughness of different geometries for different investigators are shown in tabular form. These correlations can be used to predict thermal efficiency, and hydraulic performance of roughened solar air heater ducts.

In artificially roughened solar air heaters there is a lot of scope for use of flow visualization techniques in order to analyze flow and enhancement of process. 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 enhancement of heat transfer.

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Nomenclature

A	cross-sectional area of duct, m^2
A_c	collector area, m^2
A_t	area of orifice plate at the throat, m^2
C_d	coefficient of discharge (dimensionless)
C_p	specific heat of air, J/kgK
D	hydraulic diameter of duct, m
E	height of roughness element, m
e/D	relative roughness height (dimensionless)
f	friction factor (dimensionless)
f_s	friction factor for smooth plate (dimensionless)
H	height of duct, m
I	insolation, W/m^2
Δh_1	difference of manometric fluid in U-tu manometer, m
Δh_2	difference of manometric fluid levels in micro- manometer, m
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity of air, W/m K
L	length of test section, m
S/e	Shortway length
L/e	Longway Length
m	mass flow rate, kg/s
P	pitch , m

Dimensionless Parameters

e/D	relative roughness height
f	friction factor
Nu	Nusselt Number
Re	Reynold Number
p/e	relative roughness pitch
W/H	duct aspect ratio

Greek Symbols

α	angle of attack, degree
ϕ	rib chamfer/wedge angle, dgree
μ	Dynamic viscosity, Ns/m^2