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Effect of Roughness and Glass Cover on Solar Air Heater Performance-A Review

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Abstract— *Flat plate solar air heaters are usually applied in space heating and drying processes of agricultural products, herbal medicines, clothing etc. This system occupies an important place among solar thermal systems because of minimal use of materials. A solar air heater has low heat transfer coefficient between absorber plate and the flowing air that results in higher heat losses to the environment which ultimately leads to low thermal efficiency of such thermal systems. In order to improve the heat transfer rate several methods for enhancement of thermal performance have been proposed and investigated by researchers. In the present paper the effect of artificial roughness of various geometries and glass cover on the performance of solar air heaters, investigated and analyzed by different investigators, has been mentioned. Also the results due these roughness and glass covers have been illustrated.*

Keywords— *Relative roughness pitch, (p/e); Relative roughness height, (e/D); Flow Reynolds number, (Re); Nusselt number, (Nu_{3r}); Collector roughness and flow parameters; Collector performance parameters; Collector thermal efficiency, (η_{th}); Thermo hydraulic efficiency, (η_{thermo}).*

Nomenclature

B Solar air heater duct height, m

B^{-1} stanton number roughness parameter; $B^{-1} = G_H - P_{r_t} R_M$

C^{-1} Efficiency roughness parameter; $C^{-1} = 2.5 \ln e^+ + 5.5 - R_M$

D Hydraulic diameter of solar air heater duct, m Mass Flow Rate

e Roughness height, m

e/D Relative roughness height

e^+ Roughness Reynolds number $= e/D\sqrt{\left(\frac{fr}{2}\right)}\text{Re}$

e^+_{opt} Optimal value of e^+

f Friction factor

G_H Heat transfer roughness function; $G_H = 4.5\,(e^+)^{0.28}\,p_r^{0.57}$

L^{-1} Efficiency parameter; $L^{-1} = C^{-1} - B^{-1}$

P Pitch of roughness element, m

p/e Relative roughness pitch

P_r Prandtl number

P_{r_t} Turbulent prandtl number

f_r Friction factor in rouhened collector

$\bar{f_r}$ Average friction factor

Re Reynolds number

R_M Momentum transfer roughness function; $R_M = 0.95\,(p/e)^{0.53}$

f_S Friction factor in smooth collector

S_t Stanton number

$\bar{S}_t$ Average stanton number

$\bar{S}_{tr}$ Average stanton number

W Width of solar air heater

u Velocity, m/s

u^+ Dimensionless velocity; $u/\sqrt{\tau_0/\rho}$

y Distance from the wall, m

y^+ Dimensionless distance; $(y/\upsilon)\sqrt{\tau_0/\rho}$

δ' Transition sub-layer thickness, m

δ'' Laminar sub-layer thickness, m

I. INTRODUCTION

Throughout the history of the human race, major developments have been accompanied by an increased consumption of energy. The degree of industrial advancement and prosperity of a nation is directly related to the per captain energy consumption of its people. More industrially developed countries consume more energy than developing and undeveloped countries. Those countries that have had abundant supply of energy available to them have substantially high rate of industrial growth and a corresponding high gross national product (GNP). The developing and developed countries have now to generate and harness more energy for their industrial growth and should be aware of conversion, conservation and development of new energy sources. Primitive man required energy primarily in the form of food. He derived this energy by eating plants products and animals which he hunted. Subsequently he discovered fire and his energy demand increased as he started to make use of wood and other biomass to supply the energy needs for cooking as well as for keeping himself warm, with the passage of time, man started to cultivate land for agriculture. He added a new dimension to the use of energy by domesticating and training animals to work for him, with the increasing demand of energy, man began to use the wind sailing ships and for driving wind mills and stream of water to run water wheels. The other time, the sun was supplying all the energy needs of

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man either directly or indirectly and that man was using only renewable sources of energy.

Solar energy is very vast inexhaustible resource of energy. The power from the sun intercepted by the earth is approximately 1.8 × 10^{11} MW, which is many thousands times larger than the present consumption rate on the earth of all commercial energy sources. Thus, solar energy would supply all the present and future need of the world consistently. This makes it one of the promising conventional energy sources. Scientists, engineers & power producing concerns all over the world, are trying to tap this resource.

In addition it is environmentally pollution free & available in adequate quantity in almost all parts of the world. However, there are many problems associated with its use. The major drawback with this resource is its low density. Even in the hotter region on the earth, the solar radiation flux available rarely exceeds 1 KW/m^2 and the total radiation over a day is about 7 KW/m^2. This inherent drawback requires large collection area and low efficiency. Large collection area results in excessive cost. However, a number of investigators have given their contributions for better performance of solar air heaters.

II. Effect Of Collector Parameters

Number of Cover Plates

Larger the number of cover plates reduces the thermal losses by leading to a fall in the effective transmissivity in low temperature region. At high temperature three plate covers is superior to one. Thus the number of cover plates depends upon the desired output and hence absorber temperature. The effect of the number of glasses on the solar collector efficiency has been shown in Fig. 1.1.

Glass Covers Emissivity

Low values of emissivity result in low thermal losses and thus better efficiency. Fig. 1.2 shows the influence of glass cover emissivity upon collector efficiency.

Absorber Plate Material and Geometry

Fig.1.3 shows the effect of the absorber plate material. Metallic absorber plates have higher efficiency as compare to that of the plastic ones due to their higher thermal conductivity. A tube type sheet absorber plates have high thermal conductivities which allow for thin sheets and lower conductivities can be compensated by thicker fins. Fig. 1.4 shows the combined effect of material and sheet thickness. Fig. 1.5 shows the effect of tube spacing in the absorber plate. Tube spacing has a strong effect for the case of plastic absorber plates.

Absorber Plate Selectivity

Selectivity is the ratio of absorptivity to emissivity. In order to reduce thermal losses from the absorber plate emissivity should be reduced and absorptivity should be as high as possible, as shown in Fig. 1.6.

III. Effect Of Operational Parameters

This group of parameters includes the fluid inlet and outlet temperatures and mass flow rate. These are subjected to planned variation to meet the requirements. Fig. 1.7 shows the effect of specific mass flow rate on efficiency of the collector. Higher mass flow rates leading to higher efficiency because of reduction in heat losses as larger amount of energy is transferred from the absorber decreasing its temperature. The effect of fluid inlet temperature is shown in Fig. 1.8, lower inlet temperatures yielding higher efficiencies.

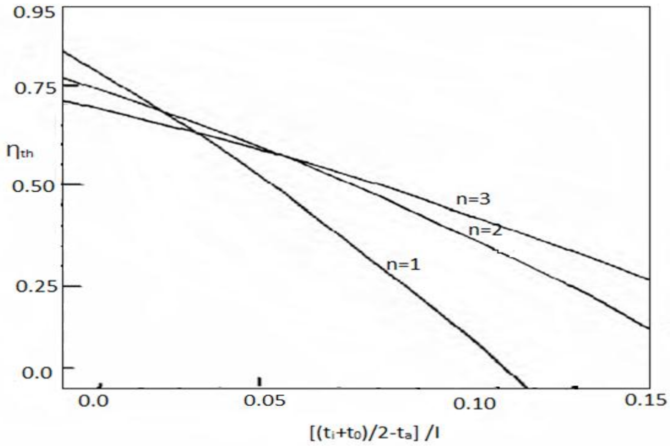

FIG. 1.1 EFFECT OF NUMBER OF COVER PLATES

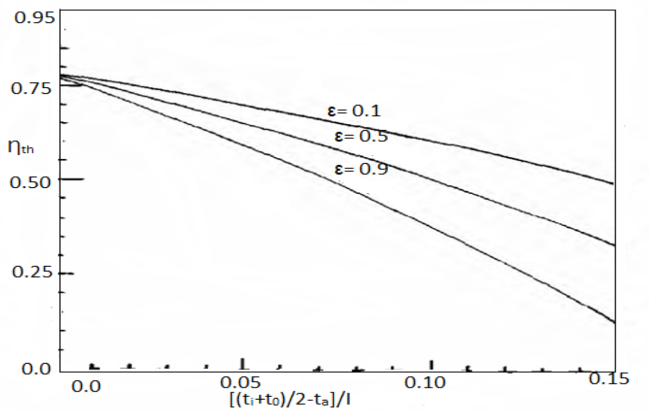

FIG.1.2 EFFECT OF GLASS EMISSIVITY

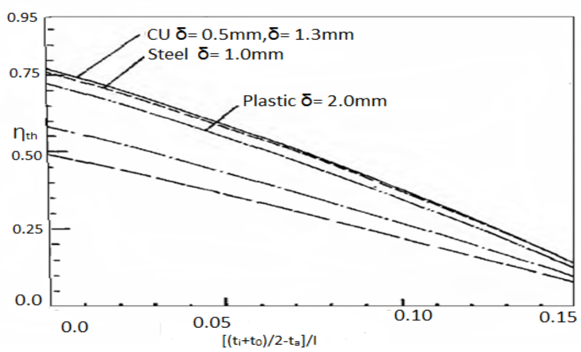

FIG.1.3 EFFECT OF MATERIAL AND THICKNESS

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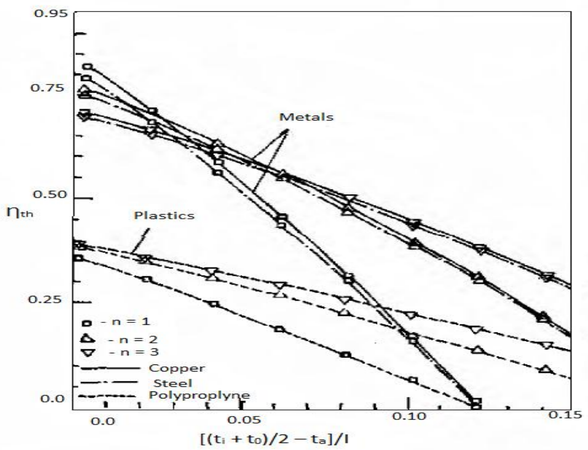

FIG. 1.4 EFFECT OF ABSORBER PLATE MATERIALS

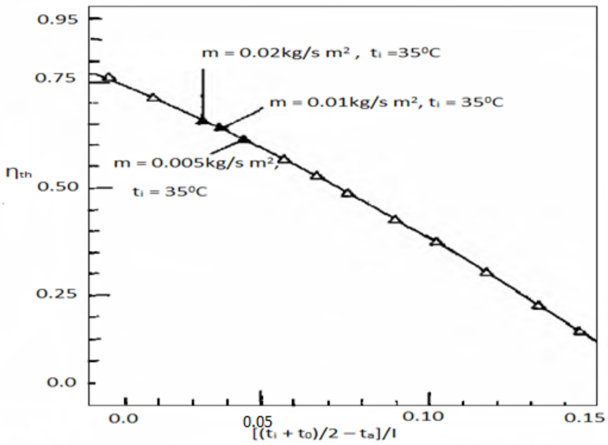

FIG. 1.7 EFFECT OF SPECIFIC MASS FLOW RATE

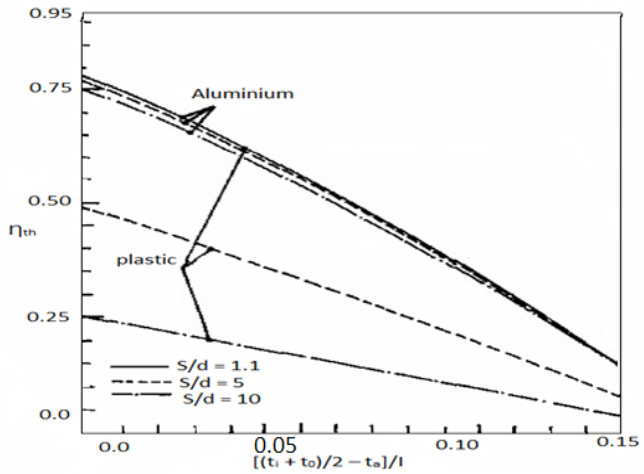

FIG. 1.5 EFFECT OF PIPE-SPACING

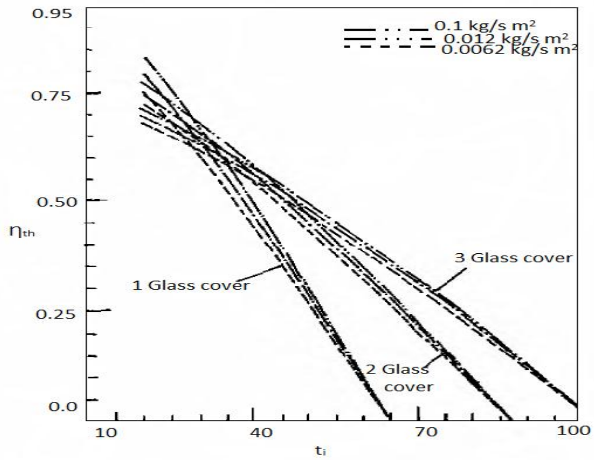

FIG. 1.8 EFFECT OF FLUID INLET TEMPERATURE AND MASS FLOW RATE

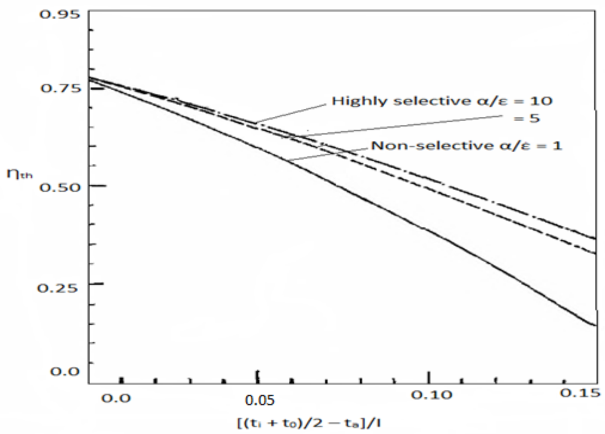

FIG. 1.6 EFFECT OF ABSORBER PLATA SELECTIVITY

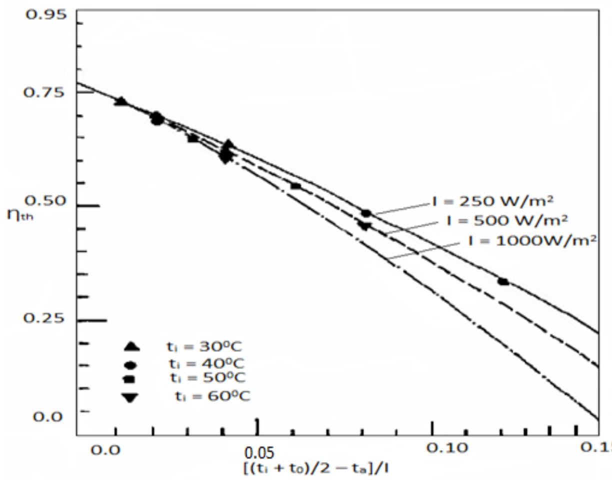

FIG. 1.9 EFFECT OF GLOBAL RADIATION

IV. EFFECT OF METROLOGICAL PARAMETERS

Global irradiation, ambient temperatures and wind speed are the important meteorological parameters which influence the collector performance to a considerable extent.

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Global Irradiation

The effect can be seen from Fig. 1.9 higher irradiations resulting in higher efficiency for the given inlet fluid temperature.

Ambient Temperature

Higher ambient temperature leads to higher efficiency under similar conditions of other parameters as can be seen from Fig. 1.10.

Wind Speed

Wind speed influences the convective heat transfer from the outside cover plate as can be seen from Fig. 1.11.

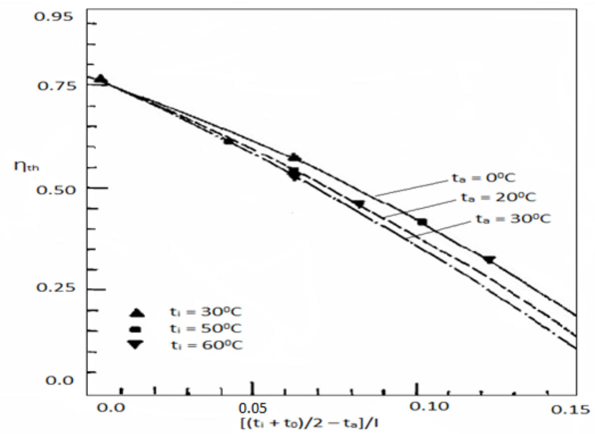

FIG.1.10 EFFECT OF AMBIENT TEMPERATUER

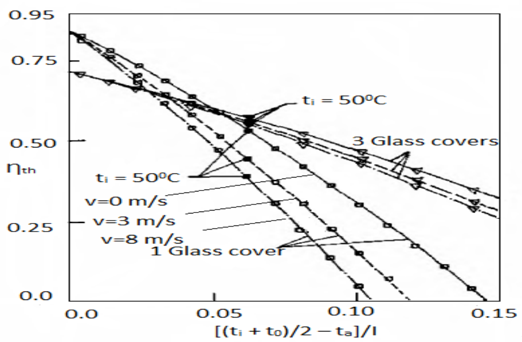

FIG.1.11 EFFECT OF WIND SPEED

V. Enhancement of Intensity of Incident Radiation

For the enhancement of intensity of incident radiation on the flat plat collectors following two methods can be taken into account:

(a) Double exposure system without booster

(b) Double exposure system with booster mirrors

In a flat plate solar collector, there is a provision of only one side absorber plate and the rear portion is insulated to reduce thermal losses. If the insulated portion is replaced by a glass cover along with a booster mirrors used for the reflection of the solar radiation onto the rear side of the collector, such a system is known as double exposure collector system. Fig. 1.12 shows the arrangement of booster mirrors with a flat plate collector.

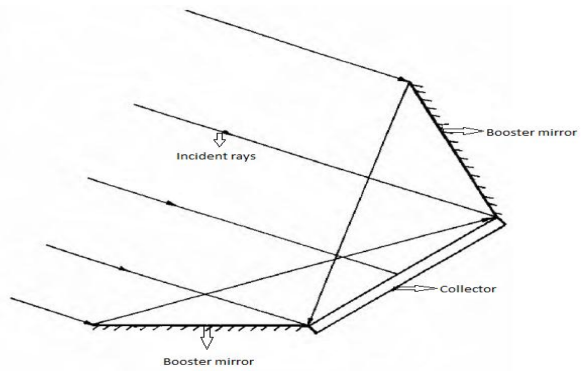

FIG. 1.12 ARRANGEMENT OF BOOSTER MIRRORS WITH A FLAT PLATE COLLECTOR

Prasad and Sah (2014), has analyzed for the enhancement in the values of radiation due to boosting on a typical hours. Fig. 1.13 shows that the intensity of radiation falling on the absorber plate increases by 40% due to boosting of radiation. The plate temperature distribution in the direction of flow duct length to see the effect of boosting of solar radiation and heat removal from the plate has been shown in Fig. 1.14. This figure also shows the effect of boosting in solar air heaters.

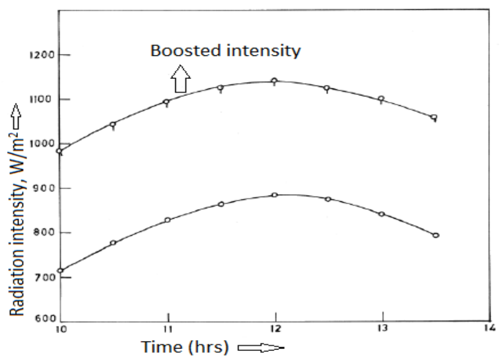

FIG. 1.13 EFFECT OF BOOSTING ON INTENSITY OF SOLAR RADIATION

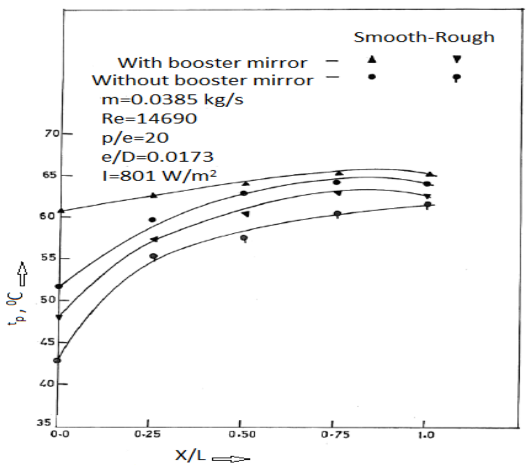

FIG. 1.14 EFFECT OF BOOSTING IN SOLAR AIR HEATERS

VI. Effect of Roughness and Flow Parameters in Solar Air Heaters

Use of artificial roughness of different configurations has been used in plenty to enhance the heat transfer rate in solar air heaters during the last decades. Varying magnitudes of roughness result in varying values of heat transfer and friction factor enhancement. The wide range of relative roughness height covered was 0.001-0.0333. The data was correlated according to the law of wall similarity, by the friction similarity function (Webb et.al., 1971, a,b).

$$u_e^+\left(e^+\right)=\sqrt{\left(2/f\right)}+2.5\ln\left(2e/D\right)+3.75 \qquad (1)$$

Dipprey and Sabersky, (1963) developed a heat momentum transfer analogy relation for flow in sand-grain roughened tubes. Three rough tubes were tested, having effective roughness ratios equal to 0.0488, 0.0138 and 0.0024 in the Reynolds number range of 60000 to 500000 in while the Prandtl number ranged from 1.2 to 5.95. The correlation developed was:-

$$\frac{\left(C_F/2C_H\right)-1}{\sqrt{\left(C_F/2\right)}}+A_f=g\left(e^+,P_r\right) \qquad (2)$$

Based on the approach considered by Han, (1984), analysis for the effect of artificial roughness was made by Prasad and Saini, (1988), for heat transfer and friction factor in a solar air heater using small diameter wire artificial roughness on the top surface, having relative roughness pitch of 10, 15, 20 and relative roughness height of 0.020, 0.027 and 0.033 to predict for a correlation for the average Nusselt number written under as:

$$\overline{Nu}=\frac{\bar{f}/2}{1+\left(\sqrt{\bar{f}/2}\right)\left[4.5(e^+)^{0.28}Pr^{0.57}-0.95(\frac{p}{e})^{0.53}\right]}Re\,Pr \qquad (3)$$

(Han et al., 1991) studied the effect of parallel and V-shaped staggered discrete ribs and found out that 60^0 staggered discrete V-shaped ribs provide higher heat transfer than that for the parallel discrete ribs. Experiments were conducted by (Lau et al., 1991 a, b, c) to study the effect of discrete V-shaped ribs on turbulent heat transfer and friction for fully developed flow of air in a square channel. They found that the average Stanton number for the inclined 45^0 and 60^0 ribs was 20-35% higher than in the 90^0 full rib cases. (Gupta et al, 1993) used transverse wire roughness on the top surface in a solar air heater to investigate for the effect of solar air heater duct aspect ratio and relative roughness height for a relative roughness pitch of 10 and flow Reynolds number of 3000-18000 to arrive at the following correlations:

For

$$e^+<35, Nu_r=0.000824(e/D)^{(-0.178)}(W/H)^{0.288}(Re)1.62 \qquad (4)$$

$$\text{For } e^+\geq 35, Nu_r=0.00307(\frac{e}{D})^{0.469}(\frac{W}{H})^{0.245}(Re)^{0.812} \qquad (5)$$

Studies conducted by Saini and Saini, (1997) deals with the effect of expanded wire mesh geometry parameter of relative long way length of mesh, relative short way length of mesh and relative roughness height of mesh on heat transfer. Comparison of thermal performance of roughened absorber plate fixed with staggered discrete V-apex (up and down) was done by (Muluwork et al., 1998, 2000). The increase of relative roughness length ratio in the range of 3-7, increases Stanton number. Boosting in Stanton number ratio was found to be of order of 1.32-2.47. (Karwa et al., 1999) developed heat transfer coefficient and friction factor correlations in rib-roughened solar air heater duct for transitional flow.

Verma and Prasad, (2000) developed the correlation for heat transfer in a top side artificially roughened solar air heater for fully developed turbulent flow as under:

$$Nu_r=0.08596(\frac{p}{e})^{-0.054}(\frac{e}{D})^{0.072}(Re)^{0.728}, \text{ for } e^+\leq 24 \qquad (6)$$

$$Nu_r=0.02954(\frac{p}{e})^{-0.016}(\frac{e}{D})^{0.021}(Re)^{0.802}, \text{ for } e^+>24 \qquad (7)$$

(Bhagoria et al., 2002) used wedge shaped transverse repeated rib roughness on one broad heated wall of solar air heater duct and generated data pertinent to friction and heat transfer. They analyzed that the presence of wedge shape ribs yield maximum enhancement in Nusselt number, about 2.4 times as compared to smooth duct. Nusselt number increases and attains maximum value at a wedge angle of about 10^0 and then sharply decreases with increasing wedge angle beyond 10^0. The correlations developed were:-

$$\overline{Nu}=1.89\times10^{-4}Re^{1.21}\left(e/D\right)^{0.426}\left(p/e\right)^{2.94}\times \exp^{\left[-0.71\left\{\ln\left(p/e\right)\right\}^2\right]}\left(\varphi/10\right)^{-0.018}\times\exp^{\left[-1.5\left\{\ln\left(\varphi/10\right)\right\}^2\right]} \qquad (8)$$

$$\bar{f}=12.44\left(e/D\right)^{0.99}\left(\varphi/10\right)^{0.49}Re^{-0.18}\left(p/e\right)^{-0.52} \qquad (9)$$

(Momin et al., 2002) experimented on flow through duct roughened with V-shape ribs attached to the underside of one broad wall of the duct, to collect data on heat transfer and fluid flow characteristics. They observed that the Nusselt number increases with an increase of Reynolds number. It was found that for relative roughness height of 0.034 and for angle of attack of 60^0, the V-shaped ribs enhance the values of Nusselt number by 1.14 and 2.3 times respectively over inclined ribs and smooth plate case at Reynolds number of 17034 and arrived the correlations as:-

$$\overline{Nu}=0.067Re^{0.888}\left(e/D\right)^{0.424}\left(\alpha/60\right)^{-0.077}\times\exp^{\left[-0.782\left\{\ln\left(\alpha/60\right)\right\}^2\right]} \qquad (10)$$

$$\bar{f}=6.266\left(e/D\right)^{0.565}\left(\alpha/60\right)^{-0.093}Re^{-0.425}\exp[-0.719\ln\left(\alpha/60\right)^2] \qquad (11)$$

Karwa, (2003) had conducted experimental study on heat transfer and friction characteristics in a high aspect ratio duct with transverse, inclined, V-up continuous and V-down continuous, V-up discrete ribs and V-down discrete ribs. He investigated that enhancement in Stanton number over smooth duct was found to be 65-90%, 87-112%, 102-137%, 110-147%, 93-134% and 102-142% respectively. The friction factor ratio for V-up continuous and V-down continuous, V-up discrete ribs and V-down discrete ribs was found to be 3.92, 3.65, 2.47 and 2.58 respectively and the correlations arrived are:

$$G = 32.26 e^{-0.006} (W/H)^{0.5} (p/e)^{2.56} \exp\left[0.7343\{\ln(p/e)\}^2\right](e^+)^{-0.08} \quad (12)$$

For $7 \le e^+ \le 20$

$$R = 1.66 (e^+)^{-0.0078} (W/H)^{-0.4} (p/e)^{2.695} \exp\left[-0.762\{\ln(p/e)\}^2 (e^+)^{-0.075}\right] \quad (13)$$

For $20 \le e^+ \le 60$

$$R = 1.325 (e^+)^{-0.0078} (W/H)^{-0.4} (p/e)^{2.695} \exp\left[-0.762\{\ln(p/e)\}^2\right] \quad (14)$$

(Cho et al., 2003) experimentally investigated the effect of gap in the inclined ribs on heat transfer in square duct with rib to pitch height ratio of 8 and angle of attack of 60^0.Experiments were carried out by maintaining the gap width same as the rib width and by varying the gap position over the duct width for parallel and cross rib arrangement on two opposite walls, they investigated that, the inclined rib with a downstream gap shows significant enhancement in heat transfer as compared to that of continuous inclined rib arrangement.

Sahu and Bhagoria, (2005) investigated effect of 90^0 broken transverse ribs on heat and fluid flow characteristics using roughness height of 1.5 mm, duct aspect ratio value of 8, pitch in the range of 10-30 mm and Reynolds number in the range of 3000-12000. Heat transfer enhancement was reported to be 1.25-1.4 times over smooth duct. From the experiment maximum thermal efficiency was found in the order of 83.5%.

The effect of relative roughness pitch, relative roughness height and relative groove position on the heat transfer coefficient and friction factor has been studied experimentally by (Jaurkur et al., 2006) using rib-grooved roughness and the correlations arrived are:

$$Nu = 0.00206 Re^{0.936} (e/D)^{0.349} (p/e)^{3.318} \exp\left[-0.868\{\ln(p/e)\}^2\right](g/p)^{1.108} \exp\left[2.486\{\ln(g/p)\}^2 + 1.405\{\ln(g/p)\}^3\right] \quad (15)$$

$$f = 0.0012 Re^{-0.199} (e/D)^{0.585} (p/e)^{7.19} \exp\left[-1.854\{\ln(p/e)\}^2\right](g/p)^{0.645} \exp\left[1.513\{\ln(g/p)\}^2 + 0.8662\{\ln(g/p)\}^3\right] \quad (16)$$

CFD investigation using ten different ribs namely rectangular, square, chamfered, triangular etc. is done by (Chaube et al., 2006). FLUENT CFD code is used for analysis using the SST k-ἐ turbulence model. The heat flux of 1100 W/m^2 is provided on the absorber plate only and rib surface is kept adiabatic. Their study reported that highest heat transfer is achieved with chamfered ribs and the best performance index is found with rectangular ribs of size 3×5.

(Karmare et al., 2007) experimentally study the effect of heat transfer performance of a rectangular duct with metal grit ribs as roughness element, employed on one broad wall, transferring heat to the air flowing through it. The effect of relative length, height and pitch of the metal grid ribs on the heat transfer and friction factor has been studied for the flow range of Reynolds numbers 4000-17000. It has been found that maximum heat transfer rate was reported for the set of parameters and maximum friction factor was observed for the set of parameters. Correlations for Nusselt number and friction factor were developed based on the experimental results and were given by:

$$Nu = 2.4 Re^{1/3} (e/D)^{0.42} (l/s)^{-0.146} (p/e)^{-0.27} \quad (17)$$

$$f = 15.55 Re^{-0.26} (e/D)^{0.94} (l/s)^{-0.27} (p/e)^{-0.51} \quad (18)$$

(Varun et al., 2008) experimentally used a combination of transverse and inclined ribs as roughness geometry and examined the thermal performance for the range of Reynolds number (Re), 2000-14000, pitch of ribs (p), 5-13 mm, roughness height (e), 1.6 mm and aspect ratio (W/H), of 10. Results show that the collector roughened with this type of roughness provides best performance at relative roughness pitch (p/e) of 8 and the correlations developed were:-

$$\bar{f} = 1.0858(Re)^{-0.3685} ({}^{p}\!/_{e})^{0.0114} \quad (19)$$

$$\overline{Nu} = 0.0006(Re)^{1.213} ({}^{p}\!/_{e})^{0.0104} \quad (20)$$

(Ahrwal et al., 2008) studied the effect of width and position of gap in inclined split-ribs having square cross section on heat transfer and friction characteristics of a rectangular air heater duct. The increase in Nusselt number and friction factor was in the range of 1.48-2.59 times and 2.26-2.9 times of the smooth duct respectively for the range of Reynolds numbers from 3000-18000 and the correlations arrived are:

$$Nu = 0.0102 Re^{1.148} (e/D)^{0.51} \left[1 - \left\{\frac{0.25 - d/w^2}{\left(0.01\left(1 - g/e\right)^2\right)}\right\}\right] \quad (21)$$

$$f = 0.5 Re^{-0.0836} (e/D)^{0.72} \quad (22)$$

Experimental study was performed by (Huang et al., 2008) for a measurement of heat transfer coefficients in a square channel with a perforation baffle on Nusselt numbers. Local heat transfer enhancement at the downstream of step baffle was found to be more significant when Reynolds number was large and when baffle height was higher. Heat transfer coefficient off centre was found to be better because of secondary flows that appeared off centre after the air flow passes through the baffle. The heat transfer enhancement in case of a baffle with holes was reported greater than that without holes.

Karwa and Maheshwari, (2009) made an experimental study of heat transfer and friction in a rectangular section duct with fully perforated baffles or half perforated baffles at relative roughness pitch of 7.2-28.8 affixed to one of the broader walls. They investigated that there was enhancement of 79-169% in Nusselt number over the smooth duct for the fully perforated baffles and 133-274% for the half perforated baffles while the friction factor for fully perforated baffles was found to be 2.98-8.02 times of that for the smooth duct and 4.42-17.5 times for the half perforated baffles. The correlations arrived are:

$$\mathrm{Nu} = 0.0893\,\mathrm{Re}^{0.7608} \tag{23}$$

$$f = 0.1673\,\mathrm{Re}^{-0.0213} \tag{24}$$

An experimental investigation had been carried out by Bopche and Tandale, (2009) to study the heat transfer coefficient and friction factor by using artificially roughness in the form of inverted U-shaped turbulators, on the absorber surface of an air heater duct. As compared to smooth one, the enhancement in heat transfer and friction factor was reported of the order of 2.82 and 3.72 times, respectively and the correlations developed are:

$$\mathrm{Nu} = 0.5429\mathrm{Re}^{0.7054}(e/D)^{0.3619}(p/e)^{-0.1592} \tag{25}$$

$$f = 1.2134\mathrm{Re}^{-0.2076}(e/D)^{0.3285}(p/e)^{-0.4259} \tag{26}$$

A 3D solar air heater duct provided with artificial roughness in the form of thin circular wire in arc shaped has been analyzed by (Kumar et al., 2009), using CFD. Renormalization k-ε̇ turbulence model is used for analysis in FLUENT CFD code. Their study reveals the maximum value of overall enhancement ratio as 1.7 for the range of parameters investigated. A parametric study of artificial roughness geometry of expanded metal mesh type in the absorber plate of solar air heater duct has been carried out by (Gupta et al. 2009). The performance evaluation in terms of energy augmentation ratio (EAR), effective energy augmentation ratio (EEAR) and exergy augmentation ratio (EXAR) has been carried out for various values of Reynolds number and roughness parameters of expanded metal mesh roughness geometry in the absorber plate of solar air heater duct. It was investigated that the augmentation ratios decrease at faster rate with Reynolds number in order of EAR, EEAR and EXAR. It was also studied that augmentation ratios increase with increase in duct depth and intensity of solar radiation. Thermal performance of wire-screen metal mesh was experimentally studied by (Paswan et al., 2009) as artificial roughness geometry on the underside of absorber plate. The thermal performance enhancement of a solar air heater was depended strongly upon the diameter of the wire and pitch, mass flow rate, insulation and inlet temperature. It was investigated that decreasing wire pitch, thermal performance of a solar air heater increases.

Sriromrein and Promvong, (2010) studied that heat transfer and friction characteristic of a rectangular duct roughened artificially with Z-shaped ribs. The enhancement in heat transfer rate and best thermal performance was reported for Z-rib inclined at 45^0. (Hans et al., 2010) developed multiple V-rib roughness and performed extensive experimentation to collect data on heat transfer and fluid flow characteristics of a roughened duct. Maximum enhancement in Nusselt number and friction factor due to presence of multi v-rib roughness has been found to be 6 and 5 times, respectively, in comparison to the smooth duct. The maximum enhancement in heat transfer has been achieved corresponding to relative roughness width (W/w) of 6. It has been observed that Nusselt number attain maximum value at 60^0angle of attack. The correlations proposed were:-

$$\overline{\mathrm{Nu}} = 3.35\times10^{-5}\mathrm{Re}^{0.92}\left(e/D\right)^{0.77}\left(W/w\right)^{0.43}\left(\alpha/90\right)^{-0.49}\times \exp^{\left[-0.1177\left\{\ln\left(W/w\right)\right\}^2\right]}\times\exp^{\left[-0.61\left\{\ln\left(\alpha/90\right)\right\}^2\right]}\left(p/e\right)^{8.54} \times\exp^{\left[-2.0407\left\{\ln\left(p/e\right)\right\}^2\right]} \tag{27}$$

$$\bar{f} = 4.47\times10^{-4}\mathrm{Re}^{-0.3188}\left(e/D\right)^{0.73}\left(W/w\right)^{0.22}\left(\alpha/90\right)^{-0.39}\times \exp\left[-0.52\left(\ln\left(\frac{\alpha}{90}\right)\right)^2\right]\left(p/e\right)^{8.9}\exp\left[-2.133\left(\ln\left(p/e\right)\right)^2\right] \tag{28}$$

(Champookham et al., 2010) carried out an experimental investigation to study the effect of combined wedge ribs and winglet type vortex generators on heat transfer and friction loss behaviors for turbulent air flow through a constant heat flux channel. Experimental investigations of heat transfer, flow friction and thermal performance factor characteristics in a tube fitted with delta winglet twisted tape, using water as working fluid was done by Eiamsa-ard et al., (2010). In the study, they described the influences of the oblique delta-winglet twisted tape and straight delta-winglet twisted tape arrangements and found that the oblique delta-winglet twisted tape is more effective turbulators giving higher heat transfer coefficient than the straight delta-winglet twisted tape. A numerical investigation had been carried out by Kwankaomeng et al., (2010) to study laminar flow and heat transfer characteristics in a 3D isothermal wall square-channel with 30^0 staggered angled-baffles. The studied the effect of different baffle heights at a single pitch ratio of 3 on heat transfer and pressure loss in the channel. The vortex flow was created by using the 30^0 angled baffle cavities leading to drastic increase in heat transfer in the channel. The order of enhancement is about 100-650% for using the angled baffles with blockage ratio of 0.1-0.3. The heat transfer augmentation was associated with enlarged pressure loss ranging from 1 to 17 times above the smooth channel. A thermal enhancement factor for the inclined baffles at blockage ratio of 0.15 was found to be highest about 2.9. (Karmare et al., 2010) had carried out analysis using CFD on solar air heater with a absorber plate roughened with metal ribs of circular, square and triangular cross-section having 54^0, 56^0, 58^0,60^0 and 62^0 inclinations to the air flow. The system and operating parameters studied were: e/D = 0.044, p/e = 17.5 and l/ s = 1.72. Range of Reynolds number was 3600-17000. Their study reported that maximum heat transfer is obtained with the square cross-section ribs 58^0 angle of attack and there is 30% enhancement in the heat transfer for square plate over smooth surface. A numerical investigation had been carried out by Promvong et al., (2010) to examine the laminar flow and heat transfer characteristics in a three dimensional isothermal wall square channel with 45^0 angled baffles. In order to generate a pair of mainstream wise vortex flows through the tested section, baffles with an attack angle of 45^0 were mounted in tandem and in-line arrangement on the lower and upper walls of the channel. Effects of different baffle heights on heat transfer and pressure loss in the channel were studied and

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results of the 45^0 in-line baffle were also compared with those of the 90^0 transverse baffle and the 45^0 staggered baffle. The effect of wedge-shaped transverse ribs roughness on flow through a rectangular duct of a solar air heater is studied using CFD by Gandhi et al., (2010). A 2D CFD simulation is carried out using FLUENT on a duct having relative roughness pitch of 4.5, relative roughness height of 0.022 and rib wedge angle of 15^0. The results of numerical analysis are in good agreement with the experimental results in terms of velocity profile and turbulence intensity.

To study the effect on the thermal performance of the ribbed channel, the parallel ribs have been installed either onto one wall of the channel or, in-line, onto two opposite walls with a rib pitch-to-height ratio ranging from 6.66-20.0. (Kumar et al., 2011) have investigated for the enhancement of heat transfer coefficient of a solar air heater having roughened air duct with a provision of artificial roughness in the form of 60^0 inclined discrete ribs. For the relative roughness pitch of 12, relative gap position of 0.35 and relative roughness height of 0.0498, the maximum heat transfer enhancement takes place. Statistical correlations for friction factor and Nusselt number have been derived as a function of gap position, rib depth, pitch and Reynolds number. The correlations have been established to predict the values of friction factor and Nusselt number with an average absolute standard deviation of 3.4% and 3.8% respectively and have been given by:-

$$\mathrm{Nu} = 3\times10^{-5}\,\mathrm{Re}^{0.947}\left({}^{e}\!/\!{}_{D}\right)^{0.29}\left({}^{p}\!/\!{}_{e}\right)^{5.885}\left({}^{d}\!/\!{}_{W}\right)^{0.115} \times\exp\left[-1.237\left\{\ln\left({}^{p}\!/\!{}_{e}\right)^{2}\right\}\right] \tag{29}$$

$$\mathrm{f} = 0.0014\,\mathrm{Re}^{-0.23}\left({}^{e}\!/\!{}_{D}\right)^{0.804}\left({}^{p}\!/\!{}_{e}\right)^{4.516}\left({}^{d}\!/\!{}_{W}\right)^{0.097}\times \exp\left[-0.944\left\{\ln\left({}^{p}\!/\!{}_{e}\right)^{2}\right\}\right] \tag{30}$$

An experimental investigation for heat transfer and friction factor was carried out by (Lanjewar et al., 2011), having the characteristics of a rectangular duct roughened W-shaped ribs, that is arranged at an inclination with respect to the flow direction. The duct used, had a width to height ratio of 8, relative roughness pitch of 10, relative roughness height of 0.03375 and angle of attack of flow of 30^0-75^0 and the correlations proposed were:-

$$\mathrm{R} = \sqrt{\left({}^{2}\!/\!{}_{f}\right)} + 2.5\ln\left({}^{2e}\!/\!{}_{D}\right) + 3.75 \tag{31}$$

$$e^{+} = \sqrt{\left({}^{f}\!/\!{}_{2}\right)}\,\mathrm{Re}\left({}^{e}\!/\!{}_{D}\right) \tag{32}$$

$$g' = \left[\left({}^{f}\!/\!{}_{2S_t}\right) - 1\right]\sqrt{\left({}^{2}\!/\!{}_{f}\right)} + \mathrm{R} \tag{33}$$

An experimental investigation was conducted by (Bhushan et al., 2011) for a range of system and operating parameters in order to analyze the effect of artificial roughness on heat transfer and friction in solar air heater duct having protrusions as roughness geometry. Maximum enhancement of Nusselt number and friction factor has been found 3.8 and 2.2 times respectively in comparison to smooth duct for the investigated range of parameters. Maximum enhancement in heat transfer coefficient has been found to occur for relative short way length (S/e) of 31.25, relative long way length (L/e) of 31.25 and relative print diameter (d/D) of 0.294. The correlations developed are:

$$\mathrm{Nu} = 2.1\times10^{-88}\,\mathrm{Re}^{1.452}\left(S/e\right)^{12.94}\left(L/e\right)^{99.2}\left(d/D\right)^{-3.9} \exp\left[-10.4\{\log\left(S/e\right)\}^{2}\right]\exp\left[-77.2\{\log\left(\frac{L}{e}\right)\}^{2}\right] \exp\left[-7.83\{\ln\left(\frac{d}{D}\right)\}^{2}\right] \tag{34}$$

$$\mathrm{f} = 2.32\,\mathrm{Re}^{-0.201}\left(S/e\right)^{-0.383}\left(L/e\right)^{-0.484}\left(d/D\right)^{0.133} \tag{35}$$

(Pomovonge et al., 2011) experimentally studied the effects of combined ribs and delta-winglet type vortex generators (DWs) on forced convection heat transfer and friction loss behaviors for turbulent air flow through a solar air heater channel. Rectangular channel with aspect ratio of 10, height of 30 mm with Reynolds number in the range of 5000-20000 was used. They reported that combined rib and the DW provides considerable heat transfer augmentations, $\frac{Nu}{Nu_0} = 2.3 - 2.6$ and also causes a moderate pressure drop increase, $f/f_0 = 4.7 - 10.1$, depending on the attack angle and Re values.

An experimental study has been carried out by (Yadav et al., 2012) to study the effect of heat transfer and friction characteristics of turbulent flow of air passing through rectangular duct which is roughened by circular protrusions arranged in angular arc fashion. The investigation reported the maximum enhancement in heat transfer and friction factor as 2.89 and 2.93 times as compared to smooth duct. The correlations arrived are:

$$\mathrm{Nu} = 0.154\,\mathrm{Re}^{1.017}\left(p/e\right)^{-0.38}\left(e/D\right)^{0.521}\left(\alpha/60\right)^{-0.213} \exp\left[-2.023\left\{\ln\left(\alpha/60\right)\right\}^{2}\right] \tag{36}$$

$$\mathrm{f} = 7.207\,\mathrm{Re}^{-0.56}\left(p/e\right)^{-0.18}\left(e/D\right)^{0.176}\left(\alpha/60\right)^{0.038} \exp\left[1.412\left\{\ln\left(\alpha/60\right)\right\}^{2}\right] \tag{37}$$

CFD analysis on solar air heater is done by (Sharma et al., 2012) using V-shaped ribs roughness on the underside of the absorber plate. Finite volume method with semi-implicit method for pressure linked equation algorithm is used for computations. Reynolds number range was from 5000-15000. The results obtained show that the combined effect of swirling motion, detachment and reattachment of the fluid were responsible for the increase of heat transfer rate during CFD analysis. Nusselt number increases and friction factor decreases with increase in Reynolds number for all combination of relative roughness height (e/D) and relative roughness pitch (p/e). An average percentage deviation predicted between CFD and exact solution was found less than $\pm 3\%$ V-shaped rib roughness found to give high rate of heat

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transfer. A numerical investigation on laminar flow and heat transfer characteristics in a 3D isothermal wall square-channel fitted with in-line 45^0 V-shaped baffles on two opposite wall was done by (Promvong et al., 2012). The in-line V-baffles with its V-tip pointing downstream and the angle of attack of 45^0 relative to the flow direction were mounted repeatedly on the lower and upper walls. The V-baffled channel flow was found to be fully developed periodic flow and heat transfer profiles at about x/D=8 downstream of the tested channel inlet. It was reported that the P-vortex flow caused by the V-baffle induced impingement flows on the channel walls leading to drastic increase in the heat transfer rate. The heat transfer in the V-baffled channel was found to be about 1-21 times higher than the smooth channel with no baffle.

Experimental investigation has been carried out by (Chauhan et al., 2013) to study heat transfer and friction factor characteristics using impinging jets in solar air heaters duct. The study shows that there is considerable enhancement in heat transfer and friction factor by 2.67 and 3.5 times respectively and the correlations arrived were:

$$Nu = 1.658\times10^{-3} Re^{0.8512} \left(X/D_h\right)^{0.1761} \left(Y/D_h\right)^{0.141} \left(D_j/D_h\right)^{-1.9854} \left[\exp - 0.3498\{\ln\left(D_j/D_h\right)\}^2\right] \quad (38)$$

$$f = \left[0.3475 Re^{-0.5244} \left(\frac{X}{D_h}\right)^{0.4169} \left(\frac{Y}{D_h}\right)^{0.5321} \left(\frac{D_j}{D_h}\right)^{-1.4848} \exp\left[-0.22210\{\ln\left(D_j/D_h\right)\}^2\right] \right] \quad (39)$$

Prasad, (2013) represented the experimental results on heat transfer and thereby thermal performance of artificially roughened solar air heaters for fully developed turbulent flow. Such solar air heaters have been found to give considerably high value of collector heat removal factor (F_R), collector efficiency factor (F') and thermal efficiency (η_{th}) as compared to the corresponding values of those of smooth collectors. In the range of the operating parameters investigated, the ratio of the respective values of the parameters F_R, F' and η_{th} for the roughened collectors to the smooth collectors have been found to be 1.786, 1.806 and 1.842 respectively and the correlations arrived were:-

$$\overline{Nu} = \left(\overline{f}/2\right) Re Pr \Big/ \left[1 + \sqrt{\left(\overline{f}/2\right)} \left\{ 4.5\left(e^+\right)^{0.28} Pr^{0.57} - 0.95\left(p/e\right)^{0.53} \right\}\right] \quad (40)$$

$$\overline{f} = \frac{2}{[0.95\left(p/e\right)^{0.53} + 2.5\ln\left(D/2e\right) - 3.75]^2} \quad (41)$$

A CFD based investigation of turbulent flow through a solar air heater is carried out by Yadav and Bhagoria, (2013, a) with square sectioned transverse rib roughness. The 2D analysis of rectangular duct is performed using ANSYS FLUENT 12.1 software and using (RNG k-ἐ) turbulence model. Analysis using four different configurations of rib roughness keeping relative roughness pitch constant at p/e = 14.29 and six different values of Reynolds number, ranging from 3800-18000, revels that the relative roughness height is a vital factor and mainly affects the rate of heat transfer rate and the increase in flow friction. An investigation has been conducted by Yadav and Bhagoria, (2013, b) by using FLUENT 12.1 and (RNG k-ἐ) turbulence model on solar air heater, using square sectioned transverse rib roughness, with different values of relative roughness pitch (7.14 ≤ p/e ≤ 17.86). 2D CFD analysis to predict the effect of small diameter of transverse wire rib roughness on heat transfer enhancement in solar air heater is done by Yadav and Bhagoria, (2013, c). In this analysis also FLUENT 12.1 software is used with (RNG k-ἐ) turbulence model. Results on thermal and thermo hydraulic performance of wavy finned absorber plate solar air heaters have been reported recently (Priyam and Chand, 2016). Chouksey and Sharma, (2016), investigated for the thermal performance characteristics of solar air heater having its duct with blackened wire screen matrices. Kumar et al., 2017e, have given a CFD analysis for solar air heater with corrugated absorber plate in which it was shown that the Renormalization-group k-epsilon model provides the results close to those, worked out from available empirical co-relation for two-dimensional steady flow solar air heaters. An energetic and exergetic approach for the performance of packed bed solar air heaters with blackened wire screen matrices pack was taken by Kumar et al., 2017f. The characteristic equations for heat transfer and fluid flow in packed bed solar air heaters have been used in order to analyze the effect of system and operating parameters on energy and energy performance. Finite difference solution algorithm has been developed to obtain numerical solutions of the governing equations. Results revealed that mass flow rate of air are a strong parameter affecting the effective and energetic efficiencies.

However, in all the above cases, the provision of artificial roughness and glass cover has remained limited to only one side (top side) of the solar air heater duct except those of the recent ones (Prasad et al., 2014; Kumar et al., 2016a, Behura et al., 2016a; Behura et al., 2017; Behura et al., 2016b; Kumar et al., 2016b; Kumar et al., 2017a), wherein it has been concluded that three sides roughened and glass covered solar air heaters perform even better than those of one side roughened and glass covered solar air heaters, but friction factor also increases. (Prasad et al., 2014) analyzed with respect to fluid flow and heat transfer in a novel solar air heater having artificial roughness on three sides (the two side walls and the top side) of the rectangular solar air heater duct, with three sides glass covers. Equations for friction factor and heat transfer parameter have been developed. The analytical values of friction factor and heat transfer parameter have been found to be 2 to 40% more and 20 to 75% more than those of the respective values of (Prasad and Saini, 1988) for the same range of the values of operating parameters p/e, e/D and Re and fixed values of W and B. The correlations developed are:-

$$\overline{Nu_r} = \frac{\overline{f}_r/2}{1 + \left(\sqrt{\overline{f}_r/2}\right)\left[4.5(e^+)^{0.28} Pr^{0.57} - 0.95(p/e)^{0.53}\right]} Re\, Pr \quad (42)$$

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$$\overline{f_r} = \frac{(W+2B)\left[\frac{2}{\left\{0.95\left(\frac{P}{e}\right)^{0.53}+2.5\ln\left(\frac{D}{2e}\right)-3.75\right\}^2}\right]+Wf_s}{2(W+B)} \quad (43)$$

Behura et al., (2016), investigated experimentally the heat transfer, friction factor and thermal performance of a novel type of three sides artificially roughened and three sides glass covered solar air heaters under fully developed turbulent flow conditions and compare well with analytical values of Prasad et al., (2014).

The effect of glass cover has been shown (Kumar et al., 2016c) by performing an investigation, that has given even better performance for three sides glass covers as compared to that of the one side glass covered one. The authors (Prasad et al., 2015), analysis could reveal that, $e^+_{opt} = 23$, corresponds to the optimal thermo hydraulic performance in three sides artificially roughened and glass covered solar air heaters, which have further been verified by taking an experimental investigation (Kumar et al., 2017b). Investigation for jet plate solar air heater with longitudinal fins has been carried out by Kumar et al., 2017c. Use of booster mirror in three sides solar air heaters for characterizing thermal performance and heat transfer & plate temperature behaviors has been introduced (Kumar, 2016a and 2016b). Further the review papers given (Ravi Kumar et al., 2016 and Kumar and Alam, 2016), may be useful in vital studies of roughness importance in the field of solar air heater performance. Correlations for three sides artificially roughened solar air heaters with transverse wires have been developed (Kumar et al., 2017d), for three sides roughened one as well as three sides glass covered solar air heaters. Correlations for Nusselt number and friction factor have been developed in terms of roughness and flow parameters as under:

$$Nu_{3r} = 0.1415(p/e)^{-0.0713}(e/D)^{0.0871}(Re)^{0.746} \quad \text{For } e^+ \le 23 \quad (44)$$

$$Nu_{3r} = 0.0422(p/e)^{-0.0461}(e/D)^{0.0375}(Re)^{1.208} \quad \text{For } e^+ > 23 \quad (45)$$

$$f_{3r} = 0.372(p/e)^{-0.319}(e/D)^{0.354}(Re)^{-1.76} \quad (46)$$

$$Nu_{3gs} = 0.0782(P_r)^{0.5}(f_s)^{0.7}(Re)^{0.932} \quad (47)$$

VII. Optimization of the System Parameters

As the enhancement of heat transfer coefficient is attempted by providing artificially roughness, it always goes with an increment of pressure drop and the requirement of pumping power is increased. So, there is a need to optimize the system parameters to maximize heat transfer while keeping friction losses as low as possible.

Despite plenty of works dealing with the effect of artificial roughness on heat transfer and friction factor in solar air heaters, very few dealt with the thermo hydraulic performance in them. The thermo hydraulic optimization parameter, $e^+ = \frac{e}{D}\sqrt{\frac{f}{2}}Re$, known as roughness Reynolds number, has been considered to arrive at the optimal thermo hydraulic performance condition. Covering a wide range of the values of heat transfer surface area, overall heat conductance and flow friction power, (Webb and Eckert, 1971), arrived at the conclusion that the value of the parameter, $e^+ = 20$, gives the optimal thermo hydraulic performance. For optimal thermo hydraulic performance of circular tube roughened with ribs, Lewis, (1975), introduced new efficiency parameters ($L^{-1}, B^{-1}, C^{-1}, G_H$ *and* R_M) and arrived at the conclusion that the value of the roughness Reynolds number $h^+ = e^+ = 20$, corresponds to the optimal thermo hydraulic condition. Sheriff and Gumbley, (1966), has studied for annulus with wire type roughness and found the value of roughness Reynolds number, $e^+ = 35$, for the optimal thermo hydraulic condition. Optimal thermo hydraulic performance analysis in one side artificially roughened solar air heater of (Prasad and Saini, 1991), has constituted a particular set of values of roughness and flow parameters to give the value of roughness Reynolds number, $e^+ = 24$, for optimal thermo hydraulic condition. Verma et al., (1991) have given a technical note on 'optimization of solar air heaters of different designs', to obtain the optimum flow channel depth and mass flow rate in 10 different designs of solar air heaters and have found that a single glazing solar air heater operating under double flow configuration gives the best performance. Hegazy, (1995) has developed an analytical criterion to determine the optimal flow channel depth of conventional flat plate solar air heaters. Gupta et al., (1997) have shown the effect of roughness parameters on the thermal as well as the thermo hydraulic performance of roughened solar air heaters to design the optimal operating conditions. A technical note on 'optimal thermo hydraulic performance of flat plate solar air heaters, operating with fixed or variable pumping power', has been given by Hegazy, (1999). Optimal thermo hydraulic performance of solar air heaters has been investigated (Verma and Prasad, 2000), for the maximum heat transfer and minimum pressure drop to arrive at the conclusion that the value of $e^+ = 24$, corresponds to the optimal thermo hydraulic performance. Saha and Mahanta, (2001) have investigated for the performance of second-law modeling of flat plate collectors with the objective of describing collector performance when entropy generation is minimum. Karwa et al., (2001) have investigated for thermo hydraulic performance of solar air heaters with chamfered repeated rib-roughness on the air flow side of the absorber plates for the range of flow Reynolds number, 3750-16350. Mittal and Varshney, (2005), has worked on optimal thermo hydraulic performance of wire mesh packed solar heater. Second law optimization of solar air heater having chamfered rib groove as a roughness element has been analyzed by Layek, et al., (2007). Karmare and Tikekar, (2008), have optimized the thermo hydraulic performance of solar air heater integrated with metal rib as roughness element. Karmare and Tikekar, (2009) have investigated for the effect of metal rib grifts on absorber plate at 60^0 of angle of attack to the flow direction of air on the thermo hydraulic performance of solar air heater. Siddhartha et al., (2012) have undertaken the work with an objective to develop and implement a trained particle swarm optimization algorithm for prediction of an optimized set of design and operating parameters for a smooth flat plate solar air heater. Yadav and Bhagoria, (2014), investigated numerically a CFD based thermo hydraulic performance analysis of an artificially roughened solar air heater having equilateral triangular sectioned rib roughness on the absorber plate. A numerical investigation is conducted to analyze the two-dimensional incompressible Navier–Stokes flows through the artificially roughened solar air heater for relevant Reynolds number ranges from 3800 to 18,000. Twelve different configurations of equilateral triangular sectioned rib (p/e=7.14 – 35.71 and e/D=0.021 – 0.042) have been used as roughness element. Sharma and Kalamkar, (2015), reviewed the thermo hydraulic performance of solar air heater having artificial roughness elements and reported the various artificial roughness geometries used by investigators to enhance the heat transfer, which is attained by increasing the pressure drop across the surfaces of the absorber plate of the solar air heater and its effect on heat transfer and friction factor through experiments.

VIII. Conclusions

On the basis of above brief description above roughness and flow parameters following are the major conclusions have been made:-

1. It can be concluded from the present review that lot of work has been carried out to investigate the effect of artificial roughness of different shapes and sizes on heat transfer and friction factor.
2. Substantial enhancement in the heat transfer can be achieved with little penalty of friction.
3. Various investigators have developed correlations for heat transfer and friction factor for solar air heater ducts having artificial roughness of different geometries.
4. These correlations can be used to predict the thermal as well as thermohydraulic performance of solar air heaters having roughened ducts.
5. Use of booster mirror to such solar air heaters may give better result as compared to the conventional one.

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