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Research Article

Theoretical prediction of performance of Single and Double pass solar air heaters with artificial roughened absorber plates

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Abstract

Investigations are carried out on artificial roughened absorber plates on Solar air heater. The roughness parameters are identified in to five basic profiles A, B, C, D and E. The profiles A, B and C are basic cubical and cylindrical profiles and the profiles D and E are categorized as rod arrangement of inline and staggered nature. Both frictional and heat transfer characteristics have been studied. Optimum results of frictional and heat transfer characteristics have been arrived out. Results show a higher value of frictional factor for the profile E. All reasons of variations have been justified and discussed. The deviation of friction factor from modified Balsius equation is within the limit of 4.32 %. Results also show higher value of Nusselt number for the inline rod arrangement of SAH than the other profiles

Keywords: *Roughened absorber plates, Solar air heater, Nusselt number, Friction factor*

1. Introduction

Solar air heaters (SAH) are extensively used in commercial and industrial applications. The research pertaining to the development of solar air a heater is enormous and has found a wide perspective in the mind of researchers. The main focus of research in the development of solar air heaters is increasing the heat transfer coefficient between the flowing air and the absorber plate of the solar air heater. Another research perspective in the development of solar air heaters are reducing the heat loss coefficient thereby indirectly increasing the efficiency of SAH. This section presents the recent developments in increasing the efficiency of SAH and the need of the present research.

Artificial roughness of absorber plates leads to a increase in thermo hydraulic efficiency (Gupta *et al* 1997) for a specific reynold's number and this kind of increase in artificial roughness needs a considerable increase in pumping power. V shaped ribs were used (Momim *et al*, 2002) in SAH. The Reynolds number (*Re*) is set to vary between 2500 to 18000 and the relative roughness is set in the range of 0.02 and 0.034. Correlations have been formulated. Broken ribs (Sahu, & Bhagoria, 2005)have been employed to increase the roughness in SAH. The nusset's number reaches its maximum for a roughness pitch value of 20 mm. The efficiency is also maximum for a roughness pitch of 20 mm. The maximum efficiency obtained is 83.5 %. It is also concluded that efficiency of SAH increases by 1.25 to 1.4 times by using roughened SAH than the smooth SAH.

Transverse wedge shaped elements (Bhagoria *et al* 2002) have been used to increase the roughness. Heat transfer was maximum for a pitch of 7.57. Multiple V ribs have been used (Hans *et al,* 2010] to increase the roughness in SAH. Arc shaped wires were used (Saini & Saini 2010) to increase the roughness. Correlations have been developed between friction factor and Nusselt number for SAH with arc like wires. Integral chamfered ribs (Karwa *et al,* 2001) have been used to enhance the roughness. Both inclined and transverse ribs (Saini & Singal 2008) have been employed to increase the roughness in SAH. The Reynold's number varied from 2000 to 14000 and the relative roughness height was taken as 0.030. Procedures to calculate thermal efficiency was formulated based on all the appending parameters.

Expanded metal mesh (Gupta & Kaushik 2009) has been suggested to improve the roughness in SAH. Performance of these kind of SAH have been analysed on the basis of Energy augmentation and exergy augmentation. It is concluded that augmentation rate decreases quickly with increase in Reynolds number (*Re*). W shaped rib absorber plates (Langewar *et al,* 2011) have been attempted to increase the roughness. Relative roughness pitch was taken as 10, relative roughness height varied between 0.018 and 0.03375. Friction factor and Nusselt number were enhanced by a maximum of 2.36 times than smoothened SAH.

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Discrete V down ribs (Singh et al 2011] are experimentally investigated in SAH. The maximum increase of friction factor and Nusselt number were observed to be 3.11 times of the Smoothened SAH. Compound turbulators (Layek *et al* 2009) were used in SAH to meet specific turbulence and roughness in SAH. Effect of chamfer angle on friction factor and Nusselt number has been obtained. Combined rib and delta winglet (Promvonge *et al* 2011) have been in the duct of SAH to enhance the roughness. The attack angle of 60° yielded the highest increase in both friction factor and Nusselt number.

Based on the literature, it is observed that there is a gap in the research of including basic dimensional elements in the absorber plate to increase the roughness. Hence, it is suggested to inculcate basic roughness geometries such as cubes, cylinders, rods etc in the SAH absorber plate to enhance the roughness in SAH.

2. Roughness Parameters and Roughness Geometries

Relative roughness pitch (p/e), Relative roughness height (e/D) and Groove position to pitch ratio (g/p) are the main parameters to determine the roughness profile of any roughed surface. The roughness geometry identified for the present study is

Cubical blocks as Roughness element on the absorber plate-Fig.1

Cylindrical blocks as Roughness element on the absorber plate-Fig.2

Rods as Roughness element on the absorber plate-Fig.3

Staggered Rods as Roughness element on the absorber plate-Fig.4

Inline Rods as Roughness element on the absorber plate-Fig.5

For Indication purpose, all the five profiles listed above are indicated as A, B, C, D and E respectively.

Fig.1. Cubical blocks as Roughness element on the absorber plate

Fig.2. Cylindrical blocks as Roughness element on the absorber plate

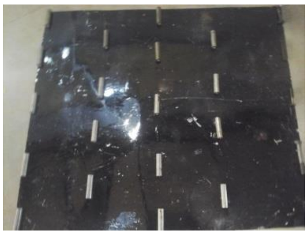

Fig.3. Rods as Roughness element on the absorber plate

Fig.4. Staggered Rods as Roughness element on the absorber plate

Fig.5. In Line Rods as Roughness element on the absorber plate

3. Range of Parameters

The parameters range employed in the present study is indicated in Table.1 The p/e value is maximum of 3.073171 for profile C and minimum of 1.046243 for profile D. The width of air duct W for all the cases is 1 m and height of air duct H for all the cases is 0.15 m.

Table.1. Relative roughness pitch values for all the profiles

Roughness Profile	Height of Rib(e)	Pitch (p)	p/e
A	10.2	15.2	1.490196
B	6.4	17.2	2.6875
C	4.1	12.6	3.073171
D	17.3	18.1	1.046243
E	17.3	18.9	1.092486

Table 2 indicates the values of relative roughness height (e/D) and groove position to pitch ratio (g/P) for all the profiles. The e/D value is maximum for profiles D and E, and minimum for profile C.

Table.2. Relative roughness height values for all the profiles

Roughness Profile	Height of Rib(e)	Equivalent Diameter, D	e/D
A	10.2	26.08	0.391104
B	6.4	26.08	0.245399
C	4.1	26.08	0.157209
D	17.3	26.08	0.663344
E	17.3	26.08	0.663344

Table 3 Indicates the range of dimension less parameters employed in this study

Table3. Dimensionless parameters value

Dimensionless parameter	Values
Reynolod's number	3000-21000
e/D	0.157209-0.663344
p/e	1.046243-3.073171
g/p	035

4. Basic Correlations and Reductions in Data

The basic correlations defining the process parameters for the study of artificial roughened absorber plates are dealt herewith. The mass flow rates (m) employed for the present study are prefixed as 0.025 kg/s, 0.020 kg/s and 0.015 kg/s. Since the study employed is of theoretical nature, the mass flow rates are assumed as above as per the earlier work carried out experimentally by (Sam Stanley *et al*, 2016)

The heat which is provided to the air is given by,

$$Q = mC_p(T_o - T_i) \quad (1)$$

The heat transfer coefficient is found out by,

$$h = \frac{Q}{A(T_p - T_f)} \quad (2)$$

The friction factor determined by this work have the following correlations. Initially as per the experimental details of a smooth duct without roughened plates, as per the experimental work carried out by (Stanley and Kalidas 2017], friction factor is initially calculated by Modified Blasius equation by,

$$f_s = 0.085\mathrm{Re}^{-0.25} \quad (3)$$

The friction factor is calculated by the below equation using pressure drop across the prefixed distance specified, equivalent diameter of the duct, density of air, length of the duct at which pressure drop is calculated and the velocity of air in the duct at which experiments and analysis are being carried out. The values of pressure drop and all relevant parameters are taken from the experimental work carried out by the same authors (Sam Stanley et al 2016) for determination of efficiency of the collector and performance comparison of different types of collector.

5. Results and discussion

5.1 Friction Factor

Table.5 indicates the value of friction factor for the artificial roughened absorber plates for the profiles A, B, C, D and E

Table.5. Friction factor for Profile A,B,C,D and E-Comparison with the modified Balsius equation

Profile	**e**	To	ΔP	ρ	Lf	V	**p/e**	f	deviation from Modified Balsius eqn
A	10.2	321	1.407705	1.0855	1	0.2303	1.490196	0.028436	4.32 %
A	10.2	322.5	1.407705	1.0804	1	0.2314	1.490196	0.028436	4.32 %
A	10.2	325	1.407705	1.0721	1	0.2332	1.490196	0.028436	4.32 %
A	10.2	326	1.407705	1.0688	1	0.2339	1.490196	0.028436	4.32 %
A	10.2	327	1.407705	1.0655	1	0.2346	1.490196	0.028436	4.32 %
B	6.4	329	1.487697	1.0591	1	0.2361	2.6875	0.030051	4.25 %
B	6.4	331	1.487697	1.0527	1	0.2375	2.6875	0.030051	4.25 %
B	6.4	334	1.487697	1.0432	1	0.2396	2.6875	0.030051	4.25 %
B	6.4	336	1.487697	1.0370	1	0.2411	2.6875	0.030051	4.25 %
B	6.4	339	1.487697	1.0278	1	0.2432	2.6875	0.030051	4.25 %
C	4.1	340	1.487697	1.0248	1	0.2440	3.073171	0.030051	4.31 %
C	4.1	341	1.570042	1.0218	1	0.2447	3.073171	0.031715	4.31 %
C	4.1	343	1.570042	1.0158	1	0.2461	3.073171	0.031715	4.31 %
C	4.1	344	1.570042	1.0129	1	0.2468	3.073171	0.031715	4.31 %
C	4.1	348	1.570042	1.0012	1	0.2497	3.073171	0.031715	4.31 %
D	17.3	348	1.570042	1.0012	1	0.2497	1.046243	0.03233	4.27 %
D	17.3	346	1.570042	1.0070	1	0.2483	1.046243	0.03233	4.27 %
D	17.3	346	1.570042	1.0070	1	0.2483	1.046243	0.03233	4.27 %
D	17.3	346	1.570042	1.0070	1	0.2483	1.046243	0.03233	4.27 %
D	17.3	346	1.570042	1.0070	1	0.2483	1.046243	0.03233	4.27 %
E	17.3	346	1.570042	1.0070	1	0.2483	1.092486	0.03341	4.18 %
E	17.3	345	1.570042	1.0099	1	0.2475	1.092486	0.03341	4.18 %
E	17.3	343	1.570042	1.0158	1	0.2461	1.092486	0.03341	4.18 %
E	17.3	339	1.570042	1.0278	1	0.2432	1.092486	0.03341	4.18 %
E	17.3	336	1.487697	1.0370	1	0.2411	1.092486	0.03341	4.18 %

The values are calculated by the equation (3) and the percentage of deviation from the equation (2) is within the limit for all the cases of profiles. The friction factor for the profile A is calculated as 0.028436. The value of e is in the range of 10.2 for profile A. The percentage deviation of the friction factor is within the limit of 4.32 % as calculated by modified Blasius equation (3) and equation (2). The p/e value for the profile A is calculated as 1.490196. For profile B, friction factor is obtained in the value of 0,030051, for a e value of 6.4 and a p/e value of 2.6875. The percentage of deviation between the friction factor calculated through equations (3) and (2) for profile B is determined and found out as 4.25 %. For the profile C, the friction factor for the roughened surface is estimated as 0.31715. The profile C has a e value of 4.1, the pressure difference for the stipulated span of measurement is 1.570042. The percentage deviation of the obtained friction factor for profile C with the values obtained from modified Balsius equation for profile C is obtained in the range of 4.31 %. The friction factor for profile D is estimated as 0.03233 and the percentage deviation from modified Balsius equation is estimated as 4.27 %. The friction factor for profile E is 0.03341 and the percentage deviation for profile E with modified Balsius equation is estimated as 4.18 %.

5.2 Heat Transfer

Heat transfer chacteristics for all the five cases of profiles viz A, B, C, D and E has to be dealt with. Nusselt number. Fig.6 indicates the variation of Nusselt number with Reynolds number for e/D value of 0.3911 and g/p value of 0.35. The value of nusselt number increases with the increasing value of Reynolds number. As Expected, nusselt number value is lower for the smooth absorber plates than the absorber plates with various roughness parameter. Also the nusselt number is maximum for the case of Profile E, Inline rods on the absorber plates. The value of profile D is lower than the value of E, this may be due to the continuous heat transfer in the inline rods arranged than the staggered rods which have lower surface area of contact than the inline arrangement of rods in Profile E.

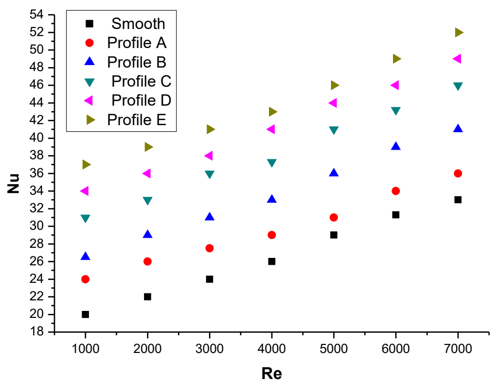

Fig.6. Nu Vs Re for e/D=0.391104 and g/p=0.35

The values of nusselt number for other profiles A, B, and C is lower than the profiles D and E. This may be due to more surface area of contact for the rod arrangement profile both staggered and inline arrangement. Fig 7. Indicates the value of variation of nusselt number with the value of p/e for various Reynolods number for g/p value of 0.35 and e/D of 0.2453. For all cases Nusselt number has a increasing trend with the relative roughness pitch. The Nusselt number is maximum for the relative roughness pitch of 3. Also the heat transfer had a maximum value for the best combination of all relevant parameters of p, e/D and p/e.

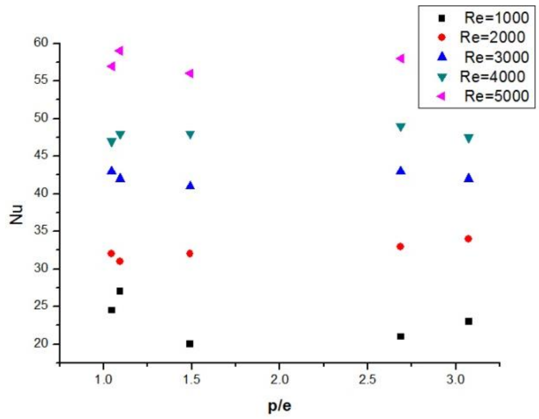

Fig.7. Nu vs relative roughness pitch for g/p=0.35 and e/D=0.2453

Conclusions

Heat transfer and frictional characteristics of artificially roughened absorber plates have been arrived out. It is provided with the following conclusion.

- Characterised values of frictional and heat transfer have been arrived out for all the five profiles A, B, C, D and E.
- The friction factor is comparatively higher for the profile E than the other profiles.
- The deviation of friction factor from the modified Balsius equation is within the limit of 4.32 %.
- For profile B, friction factor is obtained in the value of 0,030051, for a e value of 6.4 and a p/e value of 2.6875.
- Nusselt number increases with the increasing value of Reynolds number.
- The profiles D and E had comparatively higher value of Nusselt number than the other three profiles.

Nomenclature

A	area of absorber plate, m^2
e	rib height (or depth of groove), cm
e/D	relative roughness height
g	groove position between ribs, m

g/p groove position to pitch ratio
fs friction factor in smooth duct
f friction factor in roughened duct
H depth of duct, m
h convective heat transfer coefficient, W/m^2 K
k thermal conductivity of air, W/m K
Lf length of test section for pressure drop measurement, m
m mass flow rate of air in duct, kg/s
Nu Nusselt number for roughened duct
Nus Nusselt number for smooth duct
p pitch of rib (or groove), cm
Pr Prandtl number
p/e relative roughness pitch
Re Reynolds number (Re = VD/t)
D equivalent diameter of the air passage, $D=4WH/[2(W+H)]$
W width of air duct, m
H height of air channel, m
To outlet air temperature, K
Ti inlet temperature of air, K
Tp average plate temperature, K
Tf mean temperature of air, K

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