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Investigation for the Optimal Thermo Hydraulic Performance in Three Sides Artificially Roughened Solar Air Heaters

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***Abstract*—*Provision of artificial roughness on the absorber plate enhances heat transfer rate in solar air heaters, which also results in higher value of friction factor and more pumping power required. Based on the analysis (Prasad et al., 2015) for optimization of thermo hydraulic performance in three sides artificially roughened solar air heater, the present investigation deals with the results on optimal thermo hydraulic performance of such solar air heaters. The results have been represented in terms of the roughness Reynolds number, e^+, an efficiency parameter L^{-1},which combines the effect of efficiency roughness parameter, C^{-1} and Stanton number roughness parameter, B^{-1}, given by$L^{-1}=C^{-1}-B^{-1}$ and is equivalent to the thermo hydraulic performance parameter η_{thermo}. Results validate that the value of $e^+_{opt} = 23.12 \approx 23$, always corresponds to the optimal thermo hydraulic performance for such solar air heaters. It has been found that three sides roughened solar air heaters are thermally and thermo hydraulically superior than those of one side roughened solar air heaters of Prasad and Saini, (1988) and Verma and Prasad, (2000) under the same operating conditions. Optimal thermo hydraulic performance curves have been prepared to select the values of the roughness and flow parameters (p/e, e/D and Re), to design such solar air heaters to obtain optimal thermo hydraulic performance.*

***Keywords*—** *Relative roughness pitch (p/e), Relative roughness height (e/D), Stanton number roughness parameter (B^{-1}), Efficiency roughness parameter (C^{-1}), Efficiency parameter (L^{-1}) and Roughness Reynolds number (e^+).*

NOMENCLATURE

A_C collector area, m^2
B solar air heater duct height, *m*
B^{-1} Stanton number roughness parameter, $B^{-1}= G_H - P_{rt}R_M$
C^{-1} efficiency roughness parameter, $C^{-1} = 2.5\ln(e^+) + 5.5 - R_M$
C_P specific heat at constant pressure of air, KJ/KgK
D hydraulic diameter of solar air heater duct, *m*
e roughness height, *m*
e/D relative roughness height
e^+ roughness Reynolds number, $e^+ = \frac{e}{D}\sqrt{\frac{\bar{f}_r}{2}}\mathrm{Re}$
e^+_{opt} optimum value of e^+
f friction factor
f_s friction factor in smooth collector
$\bar{f}_r$ average friction factor (Prasad et al., 2015)
G_H heat transfer roughness function, $G_H = 4.5(e+)^{0.28} (P_r)^{0.57}$
g acceleration due to gravity, m/s^2
h convective heat transfer coefficient, W/m^2K
K thermal conductivity of G.I. sheet, W/mK
l length of test section, m
L collector length, m
L^{-1} efficiency parameter, $L^{-1} = C^{-1} - B^{-1}$
$\dot{m}$ mass flow rate, Kg/s
Nu Nusselt number
$\overline{Nu}_r$ average Nusselt number in three sides roughened collector
p pitch of roughness element, *m*
p/e relative roughness pitch
P_r Prandtl number
P_{r_t} turbulent Prandtl number
Re Reynolds number
R_M momentum transfer roughness function, $R_M = 0.95(p/e)^{0.53}$
S_{t_s} Stanton number for smooth collector
$\bar{S}_{tr}$ average Stanton number for three sides roughened collector (Prasad et al., 2015)
T_0 outlet temperature of air, K
T_i inlet temperature of air, K
$\bar{T}_p$ average plate temperature, K
T_f average fluid (air) temperature, K
V fluid velocity in duct, m/s
W width of solar air heater, m
ρ air density, Kg/m^3
ΔP pressure drop, N/m^2
3-Ø 3-phase
η_{thermo} thermo hydraulic efficiency parameter, $\eta_{thermo} = \frac{\left(\frac{\overline{St}_r}{St_S}\right)^3}{\left(\frac{\bar{f}_r}{f_S}\right)}$

I. INTRODUCTION

Artificial roughness has been found to enhance the rate of heat transfer from the collector plate to the flowing fluid, which also results in higher value of friction factor and more pumping power required. Artificial roughness utilized by (Prasad and Mullick, 1983) in a solar air heater in the form of small diameter wire enhanced heat transfer coefficient. Fully

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developed turbulent flow in a solar air heater duct with small diameter protrusion wire on the collector plate has been analyzed by Prasad and Saini, (1988, 1991). Gupta et al., (1997), used continuous ribs at an inclination of 60^0 to the air flow direction and found that the operating flow rate decreases with the increase in relative roughness height. By using chamfered rib roughness on the absorber plate, Karwa et al., (1999) found that at low flow rate, the solar air heater having higher relative roughness height yields a better performance. Prasad, (2013) and Prasad et al., (2014) have investigated for fully developed turbulent flow in artificially roughened solar air heater for heat transfer and friction factor. Prasad et al., (2014) analyzed for the effect of roughness and flow parameters on heat transfer for fully developed turbulent flow in three sides artificially roughened solar air heaters.

As the enactment of rate of heat transfer is attempted by providing artificially roughness, it always goes with an increment of pressure drop and the more pumping power is required. So, there is a need to optimize the system parameters to maximize heat transfer while keeping friction losses as low as possible. Analysis for the optimal thermo hydraulic performance of rough surfaces (circular tube with ribs) to heat exchanger design was made by Webb and Eckert, (1971)., covering a wide range of the values of heat transfer surface area (A), overall heat conductance (k) and flow friction power (p), to obtain the conclusion that the value of parameter, roughness Reynolds number, e^+ =20, gives the optimal thermo hydraulic performance. For optimal thermo hydraulic performance of circular tube roughened surface with ribs, (Lewis, 1975a, b); arrived at the conclusion that the value of the roughness Reynolds number 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 optimum condition. Prasad and Saini, (1991) obtained a particular set of values of roughness and flow parameters to give the value of roughness Reynolds number, e^+ = 24, for optimum thermo hydraulic condition .Optimal thermo hydraulic performance of solar air heaters has been investigated by 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. 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) has optimized the thermo hydraulic performance of solar air heater which is integrated with metal rib as roughness element. Yadav and Bhagoria, (2014) has analyzed for the optimization of thermo hydraulic performance computationally using ANSYS FLUENT, as was found to be 2.11 at e/D =0.042 and p/e =7.14 for equilateral triangular rib section at Re = 15000. Prasad et al., (2015) has analyzed for the optimization of thermo hydraulic performance in three sides artificially roughened solar air heater and found that, for a particular set of values of roughness and flow parameters, roughness Reynolds number, e^+ = 23, always corresponds to the optimized condition. The different values of optimal roughness Reynolds number, e^+_{opt}, found in literature of different roughness geometries and range of values of roughness and flow parameters for fully developed turbulent flow have been summarized in Table 1.

TABLE 1. Value of e^+_{opt} for different roughness geometries for fully developed turbulent flow

Sl No.	References	Roughness geometry type	*p/e*	*e/D*	*Re*	e^+_{opt}
1.	Sheriff and Gumley (1966)	Annulus with wires	10	———	10^4-2×10^3	35
2.	Webb and Eckert (1972)	Rectangular	10-40	0.01-0.04	6-100×10^3	20
3.	Lewis (1975a, 1975b)	Circular tubes with ribs	2-60	0.02-0.1	———	20
4.	Prasad and Saini (1991)	Rectangular duct with thin wires on one side	10-40	0.020-0.033	3-20×10^3	24
5.	Prasad et al., (2015)	Rectangular duct with thin wires on three sides	10-40	0.01126-0.0279	3–20×10^3	23

The present investigation is aimed at to develop the three sides artificially roughened solar air heater duct system for investigation under actual outdoor conditions covering a wide range of operational parameters to confirm for the optimal thermo hydraulic performance condition of e^+_{opt} =23, (Prasad et al., 2015).

II. Investigation

The experimental set-up consists of two rectangular solar air heater ducts of similar size, three sides roughened and the smooth one. Fig. 1(a) shows the four sided smooth duct and Fig. 1(b) shows the present duct model with three sided roughened and one side smooth surface. Circular wire of different diameters has been provided on the absorber plate at varying pitches to serve as an artificial roughness element. Fig. 2(a) shows typically the roughened top absorber plate with provision of artificial roughness elements on it and Fig. 2(b) shows typically a side absorber plate with artificial roughness elements on it. The experimental set-up for investigation consists of the two similar size rectangular solar air heater ducts of high aspect ratio (W>>B) as shown in Fig. 3(a). Both the ducts are having three sides' glass covers. The total length of the ducts consists of bell-mounted entry sections for flow stabilization and test sections. Mass flow rate was varied by controlling the blower speed by means of an (3-Ø) auto variac. Flange-tape orifice-meters measured the flow rates in both the solar air heaters (roughened and smooth). Since both the solar air heater ducts are similar in dimensions and are connected to a single blower to run simultaneously, mass flow rate for a particular run for both the solar air heaters measured by mean of two separate flange tape orifice-meters happened to be the same. Multi-tube manometers were used to

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measure the pressure drop, while thermocouples measured the air and plate temperatures. Intensity of solar radiation was measured by a pyranometer. Thermocouple arrangement for the top plate temperature measurement and digital thermometer for air temperature measurement inside the ducts are shown in Fig. 3 (a), while Fig. 3 (b) shows the thermocouple arrangements for top and side absorber plates of the ducts.

Test data were obtained on clear sky days between 10 AM to 2 PM during the months of April and May. A wide range of experimental data for 75 number of test runs for 15 number of roughened absorber plates were collected simultaneously with the smooth one. The roughness and flow parameters were selected so as to yield the value of the roughness Reynolds number, e^+, in the range of 8.29-34.92. Table 2 shows the range of roughness and flow parameters investigated, while Table 3 shows the detailed values of roughness parameters used in the respective 15 number of roughened absorber plates.

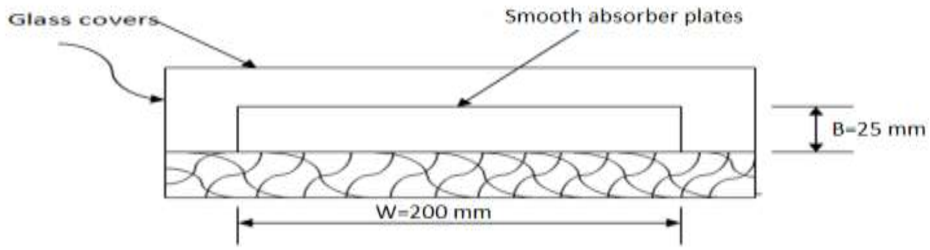

Fig. 1(a) Four sided smooth duct

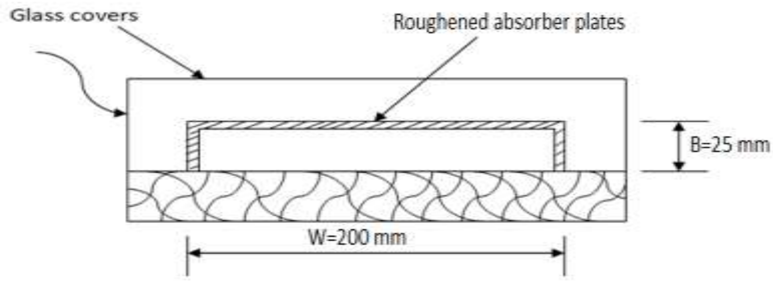

Fig. 1(b) Three sided roughened and one side smooth duct (present duct model)

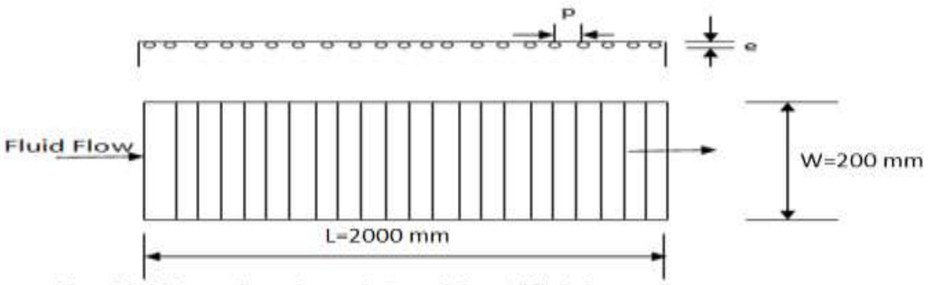

Fig. 2(a) Top absorber plate with artificial roughness

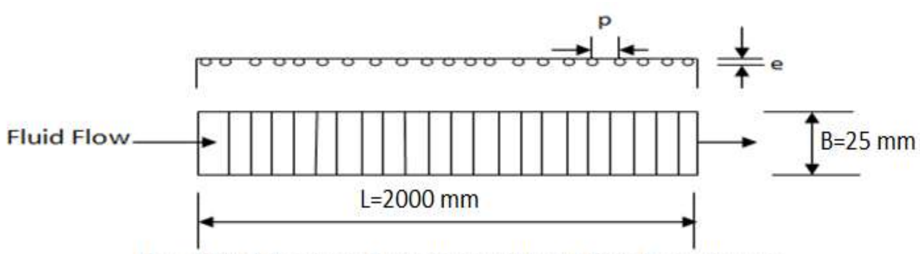

Fig. 2(b) Side absorber plate with artificial roughness

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TABLE 2. Range of parameters

Sl. No	Investigated parameters	Range of parameters
1.	Mass flow rate (Kg/s)	$8.36 \times 10^{-03} – 3.74 \times 10^{-02}$
2.	Reynolds number, Re	4000 – 20000
3.	Roughness height	0.6 mm – 1.1 mm
4.	Roughness pitch	6 mm – 30 mm
5.	Relative roughness pitch, p/e	10 – 30
6.	Relative roughness height, e/D	0.013501 – 0.024752
7.	Roughness Reynolds number, e^+	8.29 – 34.92

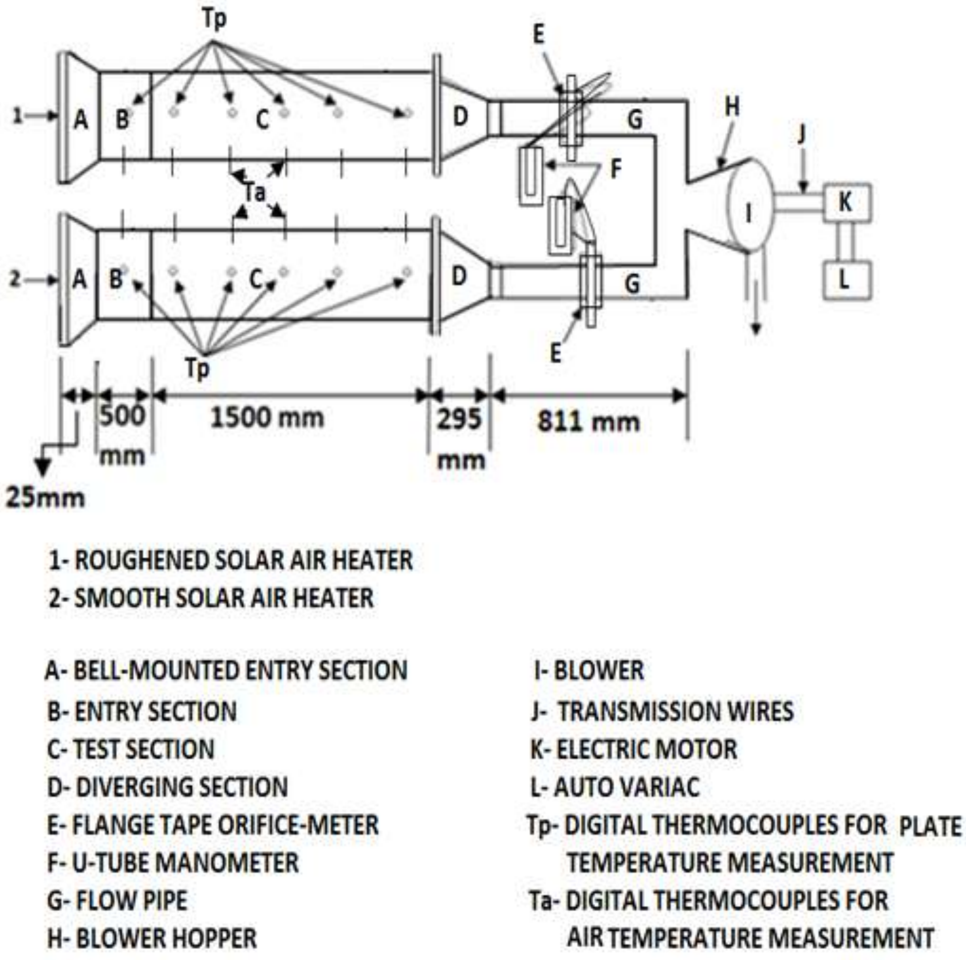

Fig. 3 (a) Schamatic diagram of experimental set-up

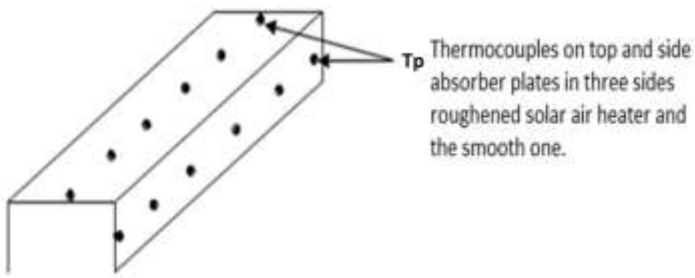

Fig. 3 (b) Thermocouple arrangement on top and sides of three sides roughened and smooth ducts

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Table 3 shows the details of roughness and flow parameters used for the investigation.

TABLE 3. Detail of roughness parameters

Plate Number	Roughness height, e (mm)	Roughness pitch, p (mm)	Relative roughness height, e/D	Relative roughness pitch, p/e
Plate no.01	1.1	11.0	0.024752	10
Plate no.02	1.1	16.5	0.024752	15
Plate no.03	1.1	22.0	0.024752	20
Plate no.04	1.1	27.5	0.024752	25
Plate no.05	1.1	33.0	0.024752	30
Plate no.06	1.0	10.0	0.022502	10
Plate no.07	1.0	15.0	0.022502	15
Plate no.08	1.0	20.0	0.022502	20
Plate no.09	1.0	25.0	0.022502	25
Plate no.10	1.0	30.0	0.022502	30
Plate no.11	0.6	06.0	0.013501	10
Plate no.12	0.6	09.0	0.013501	15
Plate no.13	0.6	12.0	0.013501	20
Plate no.14	0.6	15.0	0.013501	25
Plate no.15	0.6	18.0	0.013501	30

III. Results and Discussions

The methodology adopted to find out the thermo hydraulic results have been carried out in a similar way as those of Lewis (1975a, b); Prasad and Saini (1991) and Prasad et al., (2015). The thermo hydraulic performance equation Eq. (1) for three sides roughened solar air heater as under:

$$\eta_{thermo} = \left(\frac{\bar{S}_{t_r}}{S_{t_S}}\right)^3 \Big/ \left(\frac{\bar{f}_r}{f_s}\right) = (\bar{f}_r, G_H, R_M) \quad (1)$$

has been used to work out for the various values of the results together with the following Eqs. (2) to (5) as under:

$$\Delta P = \frac{4\rho f l V^2}{2gD} \quad (2)$$

$$\dot{m} C_P (T_0 - T_i) = h A_C (\bar{T}_P - \bar{T}_f) \quad (3)$$

$$Nu = \frac{hD}{K} \quad (4)$$

$$\bar{S}t_r = \bar{N}u_r \, Re \, P_r \quad (5)$$

Further Eq. (1) written by Eqs. (6) and (7)

$$\eta_{thermo} = \eta_{thermo}(\bar{f}_r, B^{-1}, C^{-1}) \quad (6)$$

$$\eta_{thermo} = \eta_{thermo}(\bar{f}_r, L^{-1}) \quad (7)$$

Where,

$$B^{-1} = G_H - P_{r_t} R_M = 4.5(e^+)^{0.28} P_r^{0.57} - P_{r_t} \times 0.95(p/e)^{0.53} \quad (8)$$

$$C^{-1} = 2.5 \ln(e^+) + 5.5 - R_M = 2.5 \ln(e^+) 5.5 - 0.95 \left({}^{p}/_{e}\right)^{0.53} \quad (9)$$

$$L^{-1} = C^{-1} - B^{-1} = 2.5 \ln(e^+) + 5.5 - G_H - R_M(1 - P_{r_t}) \quad (10)$$

and $e^+ = {}^{e}/_{D} \sqrt{\frac{\bar{f}_r}{2}} Re$, together with the following respective Eqs. (11) & (12) for three sides roughened solar air heater (Prasad et al., 2015) and well known Eqs. (13) & (14) for smooth solar air heater are used to work out for the values of the parameters B^{-1}, C^{-1}, and L^{-1}.

$$\bar{f}_r = \frac{(W+2B)\left[\frac{2}{\left\{0.95\left(\frac{p}{e}\right)^{0.53} + 2.5 \ln\left(\frac{D}{2e}\right) - 3.75\right\}^2}\right] + W f_s}{2(W+B)} \quad (11)$$

$$\bar{S}_{t_r} = \frac{\bar{f}_r / 2}{1 + \sqrt{\left(\frac{\bar{f}_r}{2}\right)}\left[4.5(e^+)^{0.28} P_r^{0.57} - 0.95\left(\frac{p}{e}\right)^{0.53}\right]} \quad (12)$$

$$f_S = 0.079 Re^{-0.25} \quad (13)$$

$$S_{t_s} = 0.023 Re^{0.2} P_r^{-2/3} \quad (14)$$

Table 4 represents the values of the parameters B^{-1} and C^{-1}, while Table 5 shows the values of the parameter $L^{-1} = (B^{-1} - C^{-1})$, for varying values of relative roughness pitch and roughness Reynolds number at a given value of relative roughness height. Based on the values of parameters in Table-4 & 5, Figs. 4, 5 & 6 have been drawn for comparison of the efficiency parameters B^{-1}, C^{-1}, and L^{-1}. It could be seen from these figures that the experimental values of these parameters compare well with those of the analytical values.

TABLE 4. B^{-1} and C^{-1} for the varying values of p/e at varying values of e^+

e^+	p/e = 10 B^{-1}	C^{-1}	p/e = 15 B^{-1}	C^{-1}	p/e = 20 B^{-1}	C^{-1}	p/e = 25 B^{-1}	C^{-1}	p/e = 30 B^{-1}	C^{-1}
8.29	3.852061	7.668606	3.157515	6.896899	2.566937	6.239591	2.041759	5.656059	1.554075	5.125299
11.56	4.499856	8.499859	3.71532	7.728152	3.214732	7.170842	2.689554	6.48732	2.21187	5.956552
12.86	4.720574	8.766286	4.126029	7.994579	3.435449	7.337269	2.809272	6.75378	2.432589	6.222979
17.93	5.452772	9.597171	4.758227	8.825463	4.167648	8.168153	3.64247	7.584622	3.164787	7.153863
23.12	**6.160686**	**10.23274**	**5.36615**	**9.461021**	**4.775562**	**8.803711**	**4.240384**	**8.220179**	**3.77271**	**7.689421**
25.601	6.316852	10.48757	5.62307	9.715853	5.031728	9.158543	4.40655	8.475012	4.028867	7.944253
34.92	7.143577	11.26364	6.449032	10.49193	5.858453	9.834614	5.333275	9.251083	4.855592	8.720324

TABLE 5. Efficiency parameter L^{-1} as a function of e^+ and p/e

p/e = 10		p/e = 15		p/e = 20		p/e = 25		p/e = 30	
e^+	L^{-1}	e^+	L^{-1}	e^+	L^{-1}	e^+	L^{-1}	e^+	L^{-1}
8.29	2.803911	8.29	2.726741	8.29	2.66101	8.29	2.602657	8.29	2.549811
11.56	2.819315	11.56	2.742144	11.56	2.676413	11.56	2.618061	11.56	2.564984
12.86	2.885383	12.86	2.808212	12.86	2.742481	12.86	2.684128	12.86	2.631052
17.93	2.887616	17.93	2.810446	17.93	2.744715	17.93	2.686362	17.93	2.633286
23.12	**2.899386**	**23.12**	**2.822215**	**23.12**	**2.756485**	**23.12**	**2.698131**	**23.12**	**2.645055**
25.601	2.778541	25.601	2.701371	25.601	2.635641	25.601	2.577287	25.601	2.524211
34.92	2.600535	34.92	2.523364	34.92	2.457633	34.92	2.399281	34.92	2.346204

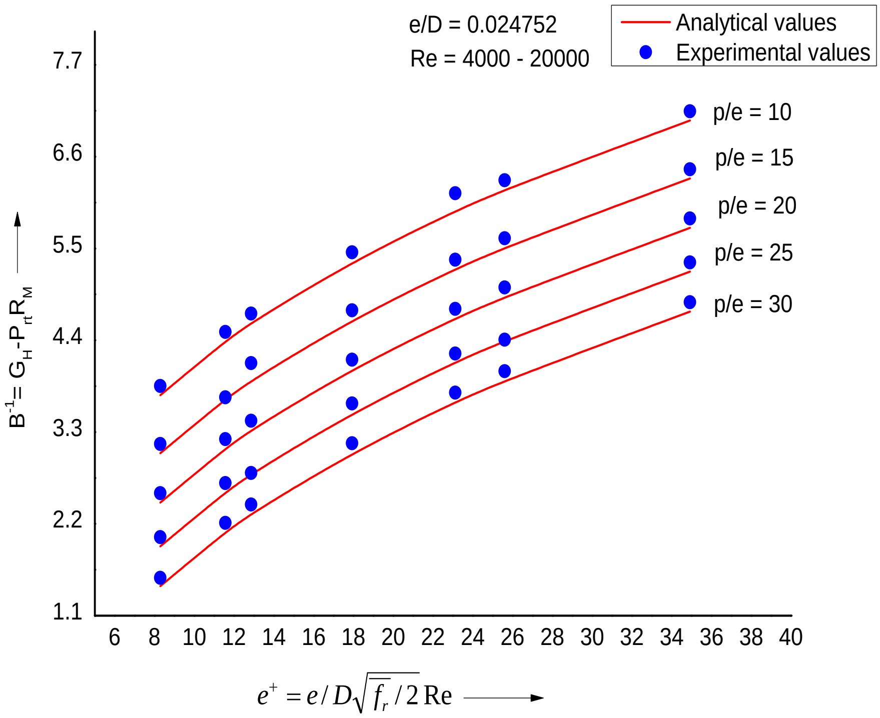

Fig.4 Comparision of B^{-1} for varying values of p/e

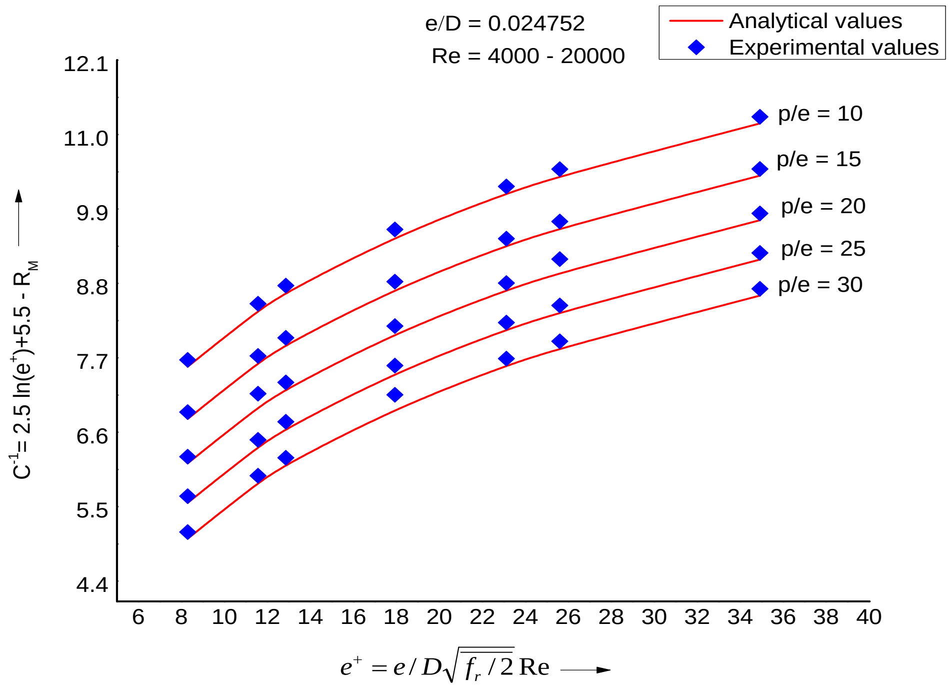

Fig.5 Comparision of C^{-1} for varying values of p/e

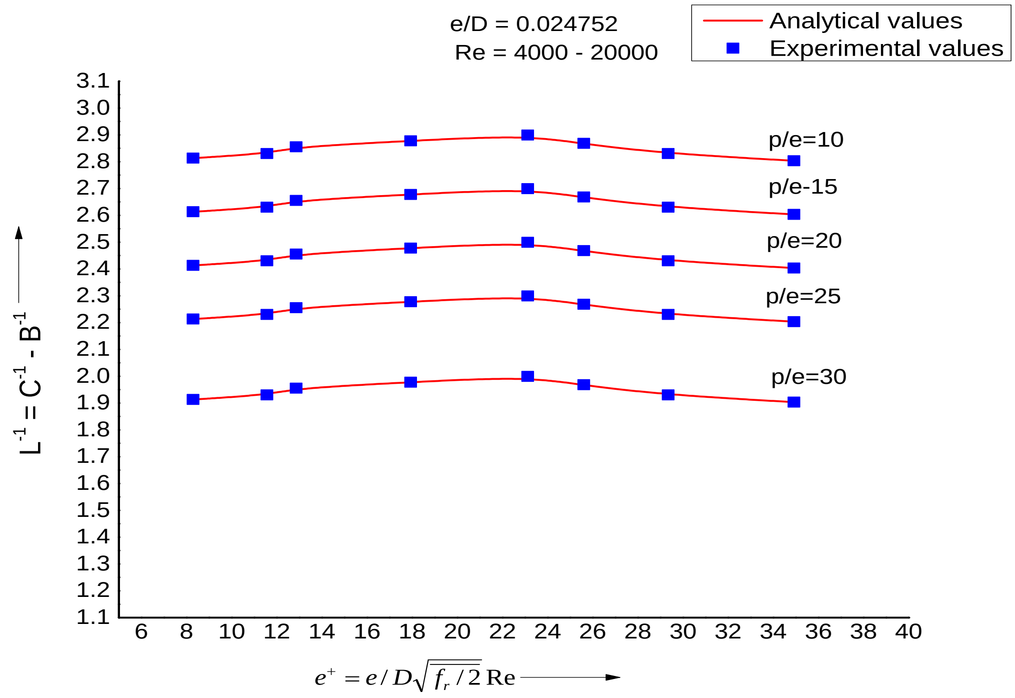

Fig.6 Comparision of efficiency parameter L^{-1} for varying values of p/e

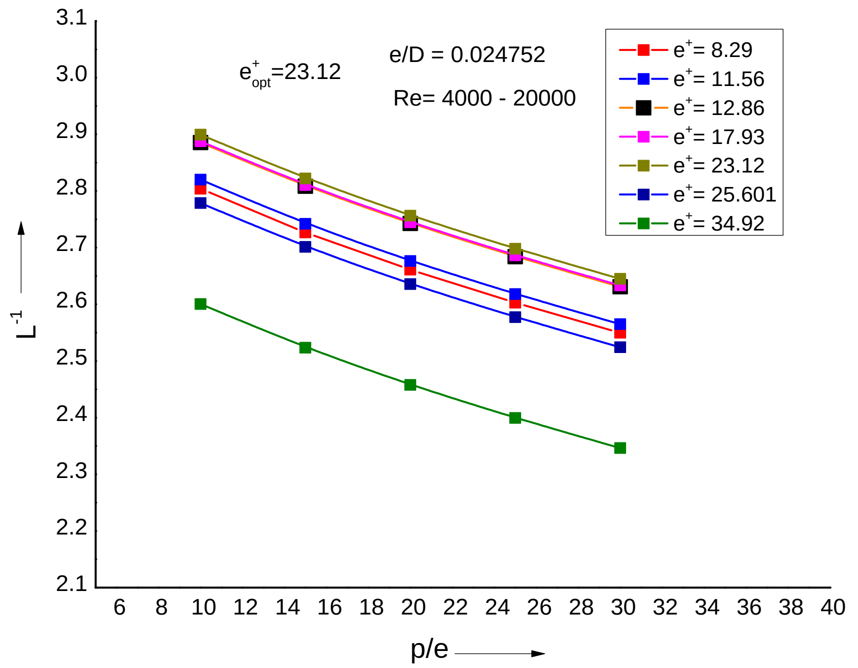

Fig.7 Efficiency parameter L^{-1} as a fuction of p/e and e^{+}

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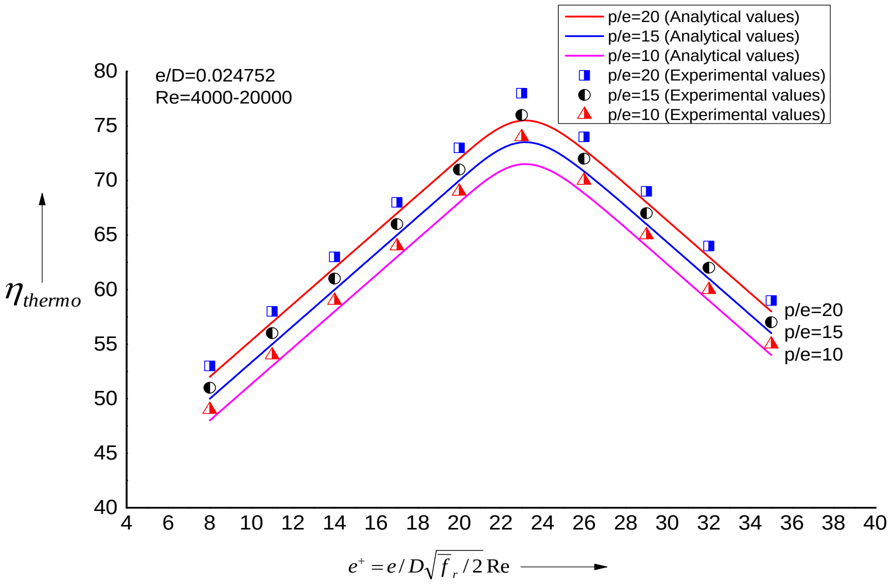

Fig.8 Efficiency versus Roughness Reynolds number

Table-6 Thermo hydraulic performance at e/D=0.024752 and Re=4000-20000

e^+	p/e =10 η_{thermo} (%)	p/e =15 η_{thermo} (%)	p/e =20 η_{thermo} (%)
8.29	49.20116	51.65134	53.41233
11.56	54.41167	56.34143	58.12312
12.86	59.10032	61.42131	63.21132
17.93	64.90451	66.71124	68.22311
20.06	69.22138	71.31012	73.21034
23.12	**74.61501**	**76.11956**	**78.81013**
26.16	70.21121	72.30129	74.11035
29.22	65.42219	67.52351	69.24123
32.27	60.60023	62.61103	64.87623
34.92	55.11632	57.51197	59.12301

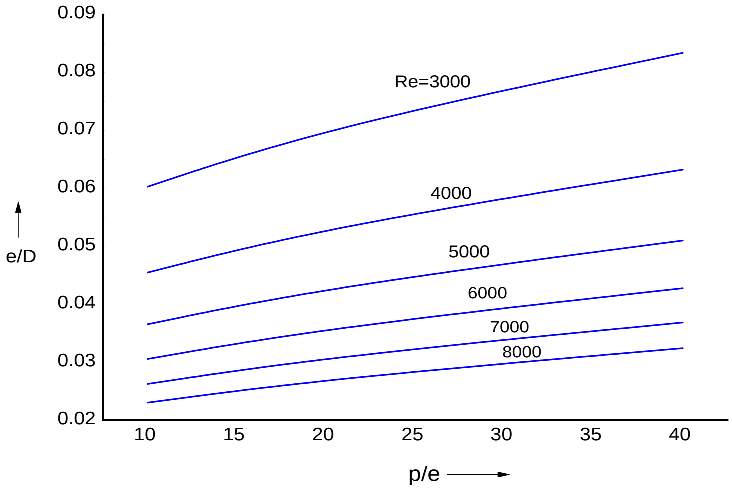

Fig.9.1 Optimal thermo hydraulic performance curve for three sides artificially roughened solar air heater

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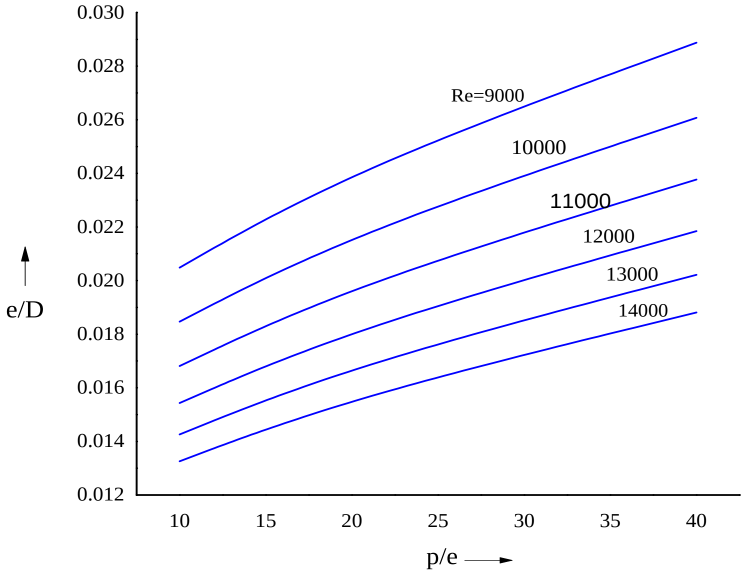

Fig.9.2 Optimal thermo hydraulic performance curve for three sides artificially roughened solar air heater

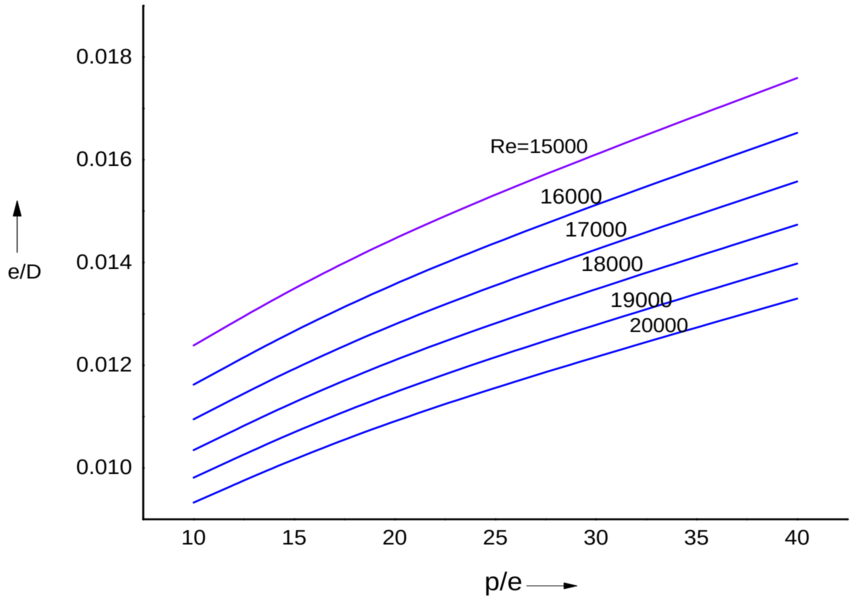

Fig.9.3 Optimal thermo hydraulic performance curve for three sides artificially roughened solar air heater

Fig. 7 has been drawn based on the values of the parameter L^{-1} (shown in Table 5) versus p/e for varying values of e^{+}, ranging from 8.29 to 34.92. It could be seen that the efficiency parameter L^{-1} attain the maximum value when $e^{+} = 23.12 \approx 23$, and therefore, $e^{+}_{opt} = 23$, gives the

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optimal thermo hydraulic performance condition. Fig. 8 has been drawn for actual values of the optimal thermo hydraulic performance, worked out by using Eqs. (1) to (5) and the analytical values worked out by using Eqs. (11) to (14). This figure shows a good agreement with the actual and analytical values for the optimal thermo hydraulic performance parameter $e^{+}_{opt} = 23$. It can therefore, concluded be that $e^{+}_{opt} = 23$, gives the set of values of the roughness and flow parameters p/e, e/D and Re to result in the optimal thermo hydraulic performance in three sides roughened solar air heaters. It has been already discussed by authors (Prasad et al., 2014) that three sides roughened solar air heaters perform better than one side roughened solar air heaters (Prasad and Saini, 1988) with respect to heat transfer and in authors' previous work (Prasad et al., 2015) it has been discussed that three sides roughened solar air heaters perform better with respect to optimal thermo hydraulic performance as compared to one side roughened solar air heaters. As such optimal thermo hydraulic performance curves of (Prasad et al., 2015) are valid to provide for the set of values of p/e, e/D and Re in three sides roughened solar air heaters for even better yield with respect to optimal thermo hydraulic performance and have been shown in Figs. 9.1 to 9.3.

From Fig. 8, it could also be seen that for the optimum roughness Reynolds number value $e^{+}_{opt} = 23$, value of optimal thermo hydraulic performance increases with increasing values of the relative roughness pitch, p/e, for a given value of relative roughness height, e/D, which has been shown in Table-6. This is because of the fact that for a given value of e/D, the rate of increase of heat transfer is more than that of friction factor for increasing values of p/e. Fig. 8 also shows the values of η_{thermo} at $e^{+} = 23.12$ for p/e = 10, 15, 20, which are maximum, confirming that $e^{+}_{opt} = 23$, gives the optimal thermo hydraulic performance.

IV. CONCLUSIONS

On the basis of the results and discussions of the present investigation the following conclusions have been drawn:-

1. Investigation for thermo hydraulic performance of three sides artificially roughened solar air heaters have been carried out.
2. An optimization parameter e^{+}, which combines the effect of flow and roughness parameters, written as $e^{+} = {}^{e}\!/\!_{D}\sqrt{\frac{\bar{f}_r}{2}}\,\mathrm{Re}$, has been considered.
3. The thermo hydraulic performance parameter $\eta_{thermo} = \dfrac{\left(\overline{St}_r / St_S\right)^3}{\bar{f}_r / f_S}$, has been considered.
4. Results validate that the optimal value of $e^{+}_{opt} = 23$, corresponds to the optimal thermo hydraulic performance in such solar air heaters.
5. The value of optimal thermo hydraulic performance in such solar air heaters increases with increasing values of relative roughness pitch, p/e, for a given value of relative roughness height, e/D.
6. The values of optimal thermo hydraulic performance have been found to be 78.81%, 76.12% and 74.61%, for p/e equal to 20, 15 and 10 respectively at a given value of e/D equal to 0.024752.
7. Three sides roughened solar air heaters are even superior to one side roughened solar air heater with respect to optimal thermo hydraulic performance under the same operating condition of mass flow rate and intensity of solar radiation.
8. The optimal thermo hydraulic performance curves are valid for the design of such solar air heaters to give optimal thermo hydraulic performance.

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