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A Study on an Optimal Thermohydraulic Performance of Three Sides Artificially Roughened and Glass Covered Solar Air Heaters

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***Abstract*— Providing artificial roughness on the air flow side is an effective technique to enhance rate of heat transfer in solar air heaters, which results in associated higher value of friction factor, which necessitates more power required. A novel solar air heater duct with three artificially roughened sides has been analyzed (Prasad et. al., 2014) for more increase in heat transfer than that in only one side roughened solar air heaters. Artificially roughened solar air heaters have been analyzed (Prasad and Saini, 1991) and investigated (Verma and Prasad, 2000) for optimal thermo hydraulic performance. The present analysis, for optimization of thermo hydraulic performance a three sides artificially roughened solar air heaters concludes that the value of optimization parameter $e^+_{opt} \approx 23.15$, gives the maximum value of heat transfer for the minimum value of friction factor.**

***Index Terms*— Relative roughness pitch (p/e), Relative roughness height (e/D), Flow Reynolds number (Re) and Roughness Reynolds number (e+).**

Nomenclature

B Solar air heater duct height, m

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

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

D Hydraulic diameter of solar air heater duct, m

e Roughness height, m

e/D Relative roughness height

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

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

$\overline{f_r}$ 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

$\overline{S}_t$ Average stanton number

$\overline{S}_{tr}$ Average stanton number (present case)

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

η efficiency parameter, defined by Eqs.(8),(9) and (10)

I.
INTRODUCTION

Flat plate collectors are widely used in low temperature energy technology and have attracted the attention to researchers in a wide range. A number of designs of solar air heater have been developed over the years to refine their enactment. The thermal efficiency of solar air heaters is usually low due to low value of heat transfer coefficient between absorber plate and flowing air which raises the absorber plate temperature, leading to higher heat loss. For the enhancement of heat transfer coefficient several investigators have contributed for several roughness geometries. (K. Prasad and Mullick, 1983) utilized artificial roughness in a solar air heater in the form of small wire to raise the heat transfer coefficient. (Prasad and saini, 1988) analyzed for fully developed turbulent flow in a solar air heater duct with small diameter profusion wire on the absorber plate. (Gupta, Solanki and Saini, 1997) used continuous ribs at inclination of 60^0 and found that the operating flow rate shifted to the lower value as the relative roughness height increases. (Karwa et. al., 1999) used chamfered rib roughness on the absorber plate and found that at low flow rate, higher relative roughness height yields a better performance.

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Fully developed turbulent heat transfer and friction factor for an artificially roughened ducts, annuli and tubes have also been widely studied by (W.Nunner, 1958; Webb Goldstein et. al., 1971; Han, 1984; Lewis, 1975; Sheriff and Gumley, 1966; Dipprey and Sabersky, 1963; V.kolar, 1964; Owen and Thomson, 1963; Donne and Meyer, 1977; Edwards and Sheriff, 1961; Webb and Eckert, 1972; Prasad and saini, 1988; B.N.Prasad, 2013). The recent work of (Prasad. B.N, Behura K.Arun and Prasad. L, 2014)., for fully developed turbulent flow heat transfer coefficient and friction factor in three sides artificially roughened solar air heater duct with a large aspect ratio (W>>B) novel one where, correlations predict the effect of roughness and flow parameters (p/e, e/D, Re) on heat transfer for fully developed turbulent flow to be even better than normal (one side roughened) solar air heaters. As the enhancement of heat transfer coefficient is attempted, 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 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, $e^+ \approx 20$, gives the optimal value.

For optimal performance of rough surface (circular tube 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 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 solution. (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 optimum condition .Optimal thermo hydraulic performance of solar air heaters has been investigated (Prasad and Verma, 2000); for the maximum heat transfer and minimum pressure drop and got the value of $e^+ = 24$. In addition, a number of investigators have shown their interest and have worked on different roughness geometries. (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), investigated for optimum thermo hydraulic performance of solar air heater with metal rib as a roughness element.

Based on the analysis (Prasad et. al., 2014), the present work deals with a methodology for thermo hydraulic optimization of three sides (top and sides) artificially roughened solar air heater for maximum heat transfer and minimum friction loss.

Methodology of optimization

The methodology of optimization adopted is similar to those of (Lewis, 1975., Prasad and Saini.1991), that a dimensionless roughness parameter, e^+ (roughness Reynolds number), could plausibly form a basis to analyze for optimal thermo hydraulic performance of artificially roughened solar air heaters with large value of aspect ratio and is based on the correlations developed (Prasad et. al.,2014), for friction factor and heat transfer in three sides artificially roughened solar air heaters, under the conditions that the law of wall similarity could be applied to both the velocity and temperature profiles, written here under as Eqs.(1) and (2) respectively:

$$\overline{f_r} = \frac{(W+2B)\,f_r + W f_s}{2(W+B)} \qquad (1)$$

$$\overline{St_r} = \frac{\overline{f_r}/2}{1+\sqrt{\left(\frac{\overline{f_r}}{2}\right)}\left[4.5(e^+)^{0.28}Pr^{0.57} - 0.95\left(\frac{p}{e}\right)^{0.53}\right]} \qquad (2)$$

Where, for W/B>>1, f_r has been substituted as that of (Webb, et. al., 1971), written under as Eq. (3)

$$f_r = \frac{2}{\left[0.95\left(\frac{p}{e}\right)^{0.53} + 2.5\ln\left(\frac{D}{2e}\right) - 3.75\right]^2} \qquad (3)$$

Consequently, Eq. (1) could be written to be Eq. (4) as under:

$$\overline{f_r} = \frac{(W+2B)\left[\frac{2}{\left\{0.95\left(\frac{p}{e}\right)^{0.53} + 2.5\ln\left(\frac{D}{2e}\right) - 3.75\right\}^2}\right] + W f_s}{2(W+B)} \qquad (4)$$

Now, Eq. (2) could be written in terms of the heat transfer function both G_H (e^+, Pr) and R_M (e^+), on the roughness geometry only and independent of the flow cross sectional area (Dalle Donne and Meyer, 1977)., as Eq. (5) under:

$$\overline{St_r} = \frac{\overline{f_r}/2}{1+\sqrt{\left(\frac{\overline{f_r}}{2}\right)}}\left[1/(G_H - R_M)\right] \qquad (5)$$

Where, $G_H = 4.5\,(e^+)^{0.28}\,p_r{}^{0.57}$ (6)

and $R_M = 0.95(p/e)^{0.53}$ (7)

The optimization parameter, η for the present case of three rough surfaces is defined as

$$\eta = \frac{\left(\frac{\overline{St_r}}{St_s}\right)^3}{\left(\frac{\overline{f_r}}{f_s}\right)} = (\overline{f_r}, G_H, R_M) \qquad (8)$$

This can further be written as:

$$\eta - (\overline{f_r}, B^{-1}, C^{-1}) \qquad (9)$$

This could further also be represented as:

$$\eta = \left(\bar{f_r}, L^{-1}\right) \quad (10)$$

Where,

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

(11)

$$C^{-1} = 2.5 \ln e^+ + 5.5 - R_M = 2.5 \ln e^+ + 5.5 - 0.95\,(\mathrm{p/e})^{0.53} \quad (12)$$

$$L^{-1} = C^{-1} - B^{-1} \quad (13)$$

$$\Rightarrow L^{-1} = 2.5 \ln e^+ + 5.5 - G_H - R_M\left(1 - P_{r_t}\right) \quad (14)$$

Also, that, the following equations could be used:

$$f_S = 0.079\,\mathrm{Re}^{-0.25} \quad (15)$$

$$St_s = 0.023 Re^{0.2} P_r^{-2/3} \quad (16)$$

$\bar{f_r}$, f_s and St_s can be calculated by using Eqs. (3), (15) add (16) respectively. Under prescribed assumption for W & B, p/e (10 - 40) and e/D has been selected in such a way that the roughness height is in the order of or slightly greater than laminar sub layer thickness and has found the optimum condition at $\mathrm{e}^+_{\mathrm{opt}} \approx 23$ (optimum roughness Reynolds number) which has been shown in Figs. 1, 2,3 & 4 and Table (1).And also, Figs.1 &2 show the comparative variation of effect of roughness Reynolds number (e^+) for different values of relative roughness pitch (p/e) on Stanton number roughness parameter (B^{-1}) and efficiency roughness parameter (C^{-1}) respectively for present and referred (Prasad and Saini,1991) cases.

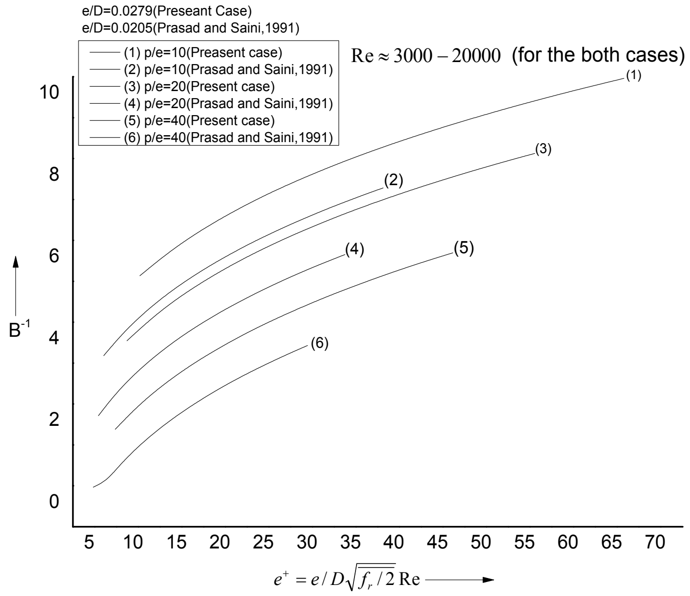

Fig. 1. Effect of e^+ on B^{-1} for varying p/e

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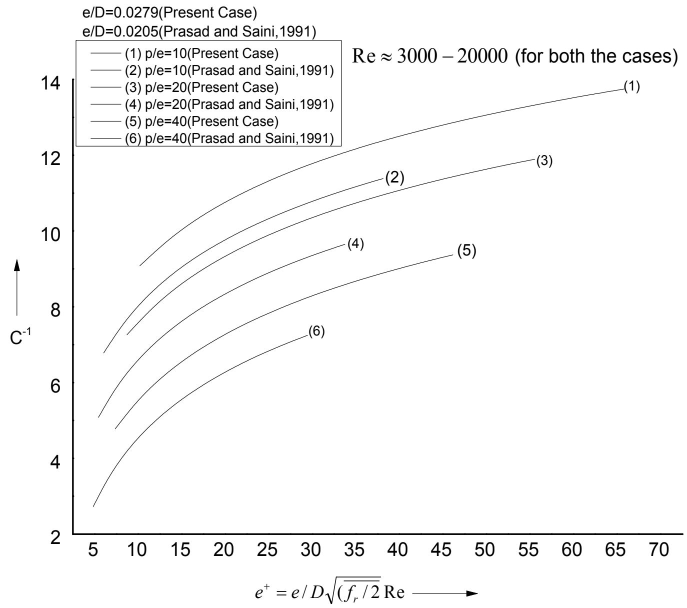

Fig. 2. Effect of e^+ on C^{-1} for varying p/e

It is obvious from Figs.1&2 that, both the parameters (B^{-1} and C^{-1}) have greater values for present case as compare to (Prasad and saini, 1991) and as L^{-1} is the function of B^{-1} and C^{-1}, the variation of e^+ on efficiency parameter (L^{-1}) for varying values of p/e would be greater than referred case, which has been shown in Fig.3 for $Re \approx 3000 - 20000$.

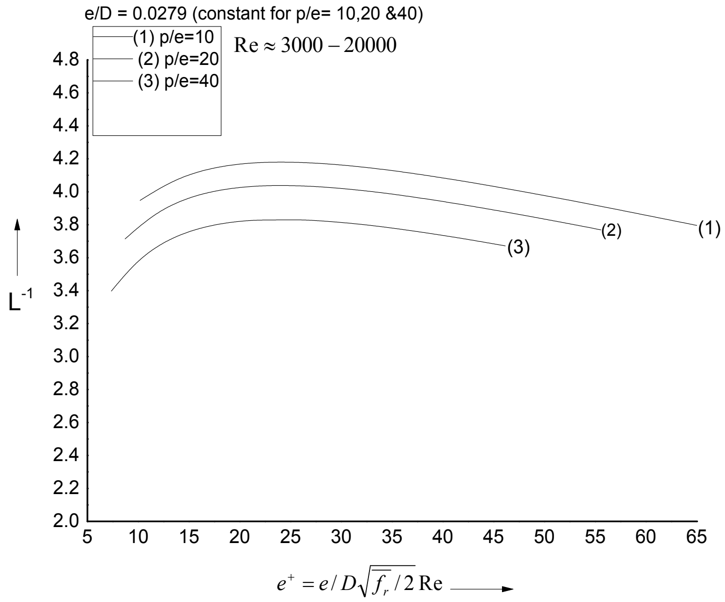

Fig.3. Effect of e^+ on L^{-1} for varying p/e

Here roughness Reynolds number ($e^+ = e/D\sqrt{f_r/2}\ Re$) Constitutes a specific set of values of roughness and flow parameters p/e, e/D, Re to obtain $e^+_{opt} \approx 23$. These set of values vary with variance in either of values of p/e, e/D, Re, individually, which has been shown in the form of design curves to give the optimal thermo hydraulic performance of three sided artificially roughened solar air heater.

Table (1) Range of efficiency parameter L^{-1} as a function of e^+ and p/e

P/e = 10		P/e =20		P/e =40	
e^+	L^{-1}	e^+	L^{-1}	e^+	L^{-1}
17	4.143224	17	4.000322	17	3.793982
22	4.180075	22	4.037173	22	3.830833
23	**4.181923**	**23**	**4.039021**	**23**	**3.832681**
24	4.177088	24	4.034186	24	3.827846
25	4.181683	25	4.038781	25	3.832441
26	4.179871	26	4.036969	26	3.830629
28	4.17343	28	4.030528	28	3.824188
30	4.163822	30	4.02092	30	3.81458
34	4.137277	34	3.994375	34	3.788035

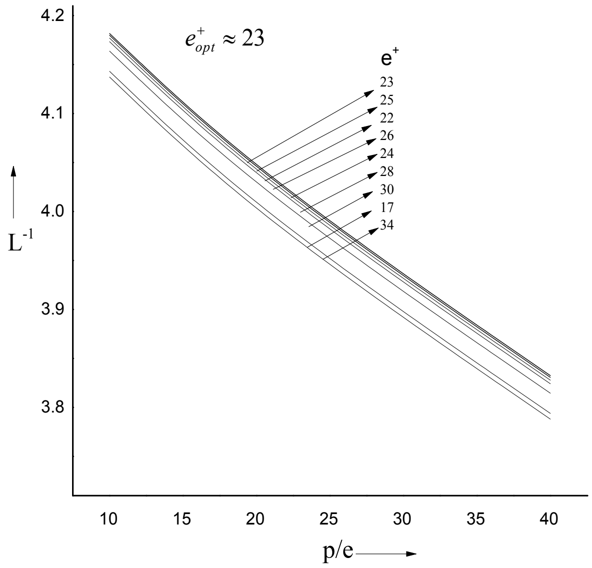

Fig.4. The efficiency parameter L^{-1} as a function of p/e & e^+

Now, the optimal thermo hydraulic performance equation may be given by:

$$e^+_{opt} = e/D\sqrt{f_r/2}\,Re = 23 \qquad (17)$$

This forms the base for optimal performance curves for the roughness and flow parameters. The values of $\bar{f}_r$ have been calculated from Eqs. (4) & (15). For the given values of parameters, Re=3000-20000; p/e=10-40 and values of e/D have been calculated by using Eq. (17) and the results have been presented in the form of design curves as shown in Figs. 5.1,5.2 &5.3.

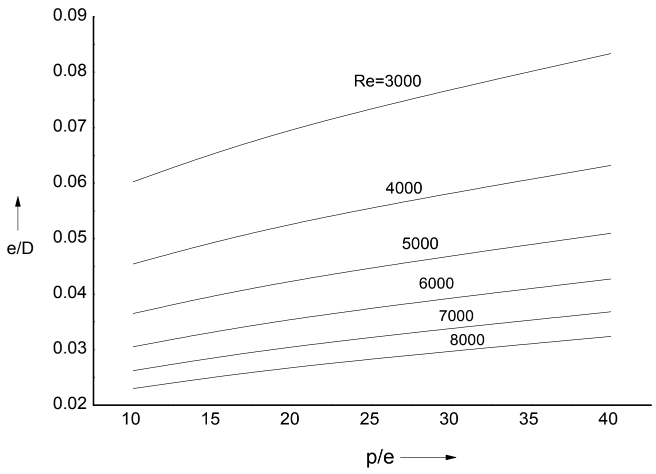

Fig.5.1 Optimal thermohydraulic performance curve for three sides artificially roughened solar air heater for Re=3000 to 8000.

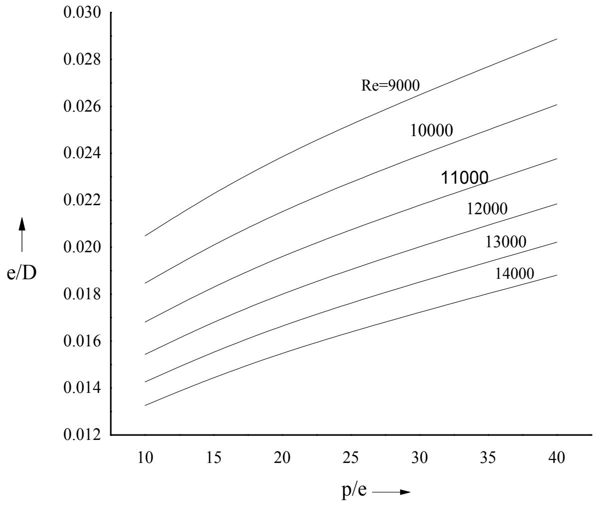

Fig.5.2 Optimum thermohydraulic performance curve for three sides artificially roughened solar air heater for Re=9000 to 14000

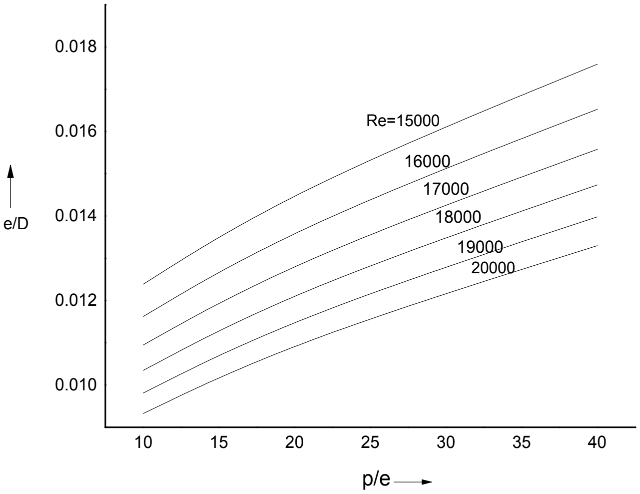

Fig.5.3 Optimum thermohydraulic performance curve for three sides artificially roughened solar air heater for Re=15000 to 20000

Results and Discussions

Fig. 5 shows the range of optimal values of e/D as a solid function of Re and p/e, however the values monotonously increasing with the increase in p/e beyond 10 and decreasing with increase in Re, and therefore; the optimum roughness parameters are selected according to the flow condition of the system. The range of optimum values of e/D as a function of Re in the relative roughness pitch range of $10 \leq p/e \leq 40$ has been shown in Fig.6. Therefore the choice appears to be wider at low flow Reynolds number but at high flow Reynolds number the effect of p/e appears to vanish. For a given Re and for p/e in the range of $10 \leq p/e \leq 40$, the optimal range of e/D is fixed, which has also been shown in Fig.6. Fig.5.gives the optimal range of e/D for Re=7000, that lies between 2.6232×10^{-2} and 3.6825×10^{-2} .It has been seen that for $e/D > 3.6825 \times 10^{-2}$, the roughness height protrude so much in hydrodynamic boundary layer, and for $e/D < 2.6232 \times 10^{-2}$ in combination with p/e < 10, reattachment of free shear layer is absent. Both the above conditions are not propitious because a high protrude roughness element leads to so high pressure drop without adding correspondingly to heat gain, but the non-reattachment of free shear layer reduces the heat transfer drastically, (Edwards and Sheriff,1961) and (W.H.Emerson,1966)., and therefore both the conditions result in the degradation of the performance.

In order to explain the effect of roughness height it has been shown (M.Necati Ozisik, 1985) that for hydro- dynamically smooth condition, roughness heights are too small that all protrusions lie within the laminar sub-layer and there is no effect of roughness. For this, only laminar shear stress is dominant and the turbulent shear stress has no existence. The expression for laminar shear stress is given by:

$$\tau_0 = \mu \delta u / \delta y = \rho \nu \delta u / \delta y \qquad (18)$$

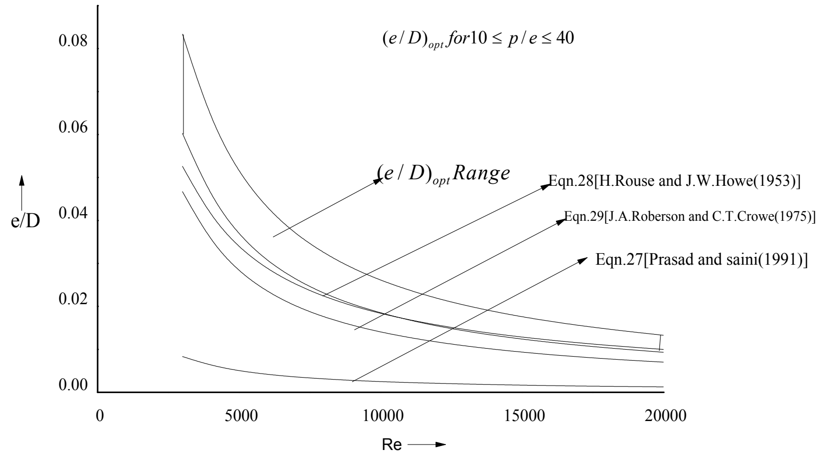

Fig.6. Optimal range of e/D

On solving Eq. (18), for constant τ_0 and u=o, at y=0, we have,

$$y = \rho v u / \tau_0 \tag{19}$$

In terms of dimensionless parameters y^+ and u^+, the linear velocity profile of laminar sub-layer is given by: $u^+ = y^+; 0 < y^+ < 5$

i.e., $u/\sqrt{\tau_0/\rho}$ or, $y/v\sqrt{\tau_0/\rho} < 5$ (20)

Or, $$\tau_0 = u^2 \rho / 25 \tag{21}$$

Eqs. (19) & (21) yield

$$y = 25 v / u \tag{22}$$

Eq. (22) gives the laminar sub-layer thickness for hydro- dynamically smooth condition in terms of Re may be written as:

$$y/D = 25/\mathrm{Re} \tag{23}$$

By replacing 'y' to 'δ''' (laminar sub-layer thickness) Eq. (23) may be rewritten as:

$\delta''/D = 25/\mathrm{Re}$ (Prasad and Saini, 1991) (24)

The value of this parameter has been shown in Fig.6, which defines the limit of laminar sub-layer. As, there is no well-defined line of demarcation between turbulent and laminar flow, the dimension δ' therefore arbitrarily represents the distance from the boundary at which the flow changes from predominantly laminar to being predominantly turbulent (Rouse and Howe,1953)., (N.B.Webber,1965) and (H. Rouse,1946). Here the dimension $\delta' = y^+ = 11.84$ (the intersecting point of the linear and logarithmic profiles of velocity), as shown in Fig.7. (Roberson and Crowe, 1975).

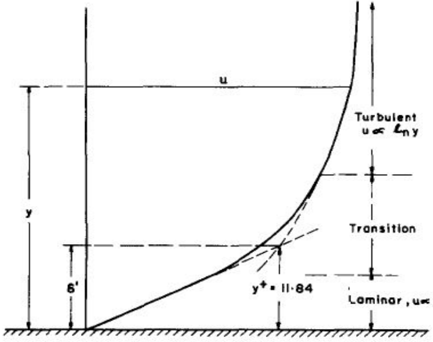

Fig.7 Velocity distribution adjacent to wall.

An expression for δ' in terms of hydraulic diameter has been given by, (Rouse and Howe, 1953)

$$\delta' / D = 58 / \mathrm{Re}^{7/8} \tag{25}$$

(Roberson and Crowe, 1975)., had given the value of y^{+} as 11.84, which gives the value of δ' as:

$$\delta' / D = (11.84)^{2} / \mathrm{Re} \tag{26}$$

The values of δ' / D given by Eqs. (25) & (26) have been plotted in Fig.6, which shows that the optimum values of e/D are higher than the value of δ' / D obtained from Eqs. (25) & (26), which indicate that the optimum roughness height (e) is slightly greater than δ'. Fig.8 shows the physical flow conditions obtained in the system, in which Fig.8 (a) shows no effect on roughness at $e << \delta'$, Figs.8 (b & c) show at $e \geq \delta'$, that the artificial roughness is such that it disturbs the region beyond the transition limit into turbulent, without interfering into the turbulent core and show the optimum condition and Fig.8 (d) shows at $e >> \delta'$, that roughness has more effect on fluid pressure as compared to heat transfer, as it disturbs the turbulent core leading to high friction loss without corresponding enhancement of heat transfer.

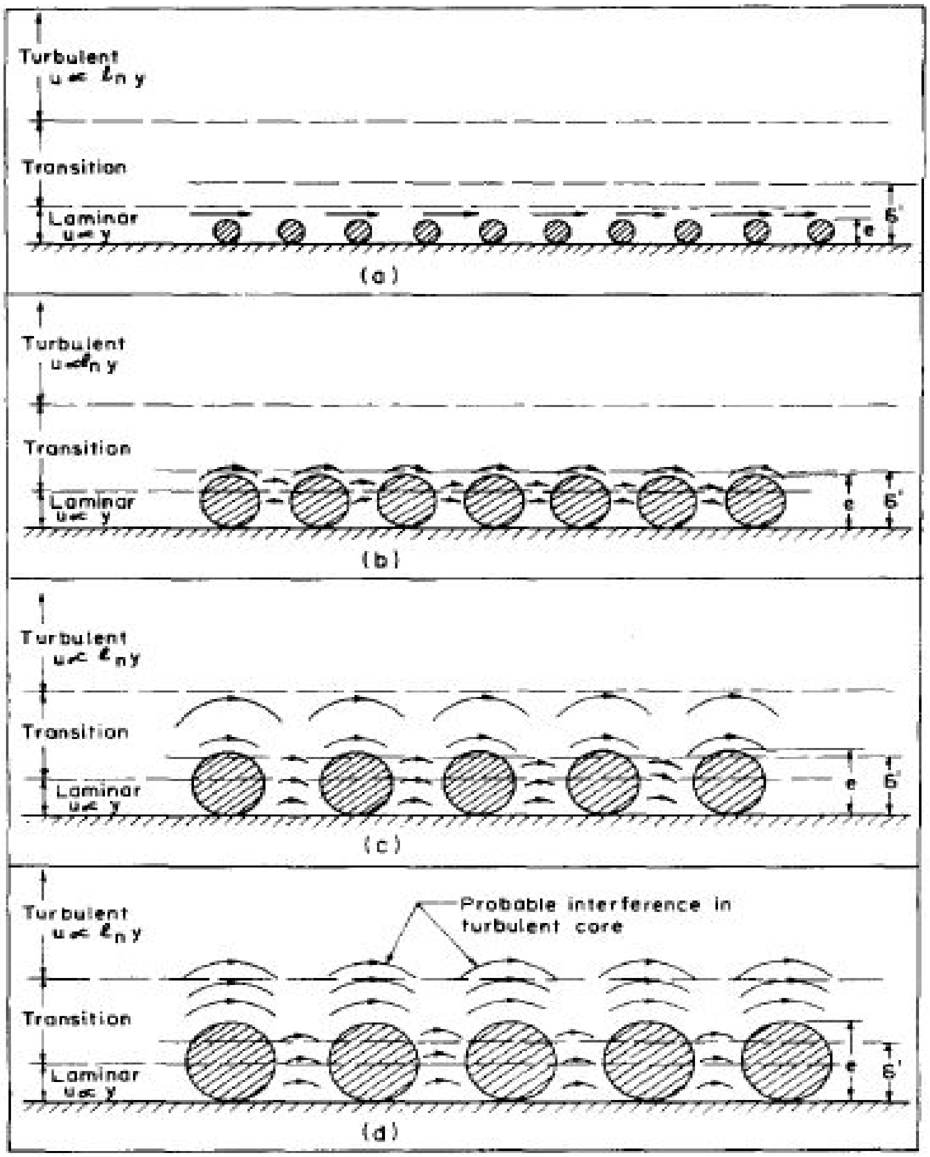

Fig.8. Effect of height on the laminar sub-layer. $(a)\ e << \delta'.(b)\ e \approx \delta'.(c)\ e \geq \delta'(optimum\ condition).(d)\ e > \delta'$.

Table (2) Values of e^{+}_{opt} found for different roughness geometries

Sl.No.	References	Roughness geometry type	p/e	e/D	Re	e^{+}_{opt}
1.	Sheriff and Gumley (1966)	Annulus with wires	10	——	$10^4 - 2\times10^3$	35
2.	Webb and Eckert (1972)	Rectangular	$10-40$	0.01-0.04	$6-100\times10^{-3}$	20
3.	Lewis (1975)	Circular tubes with ribs	——	——	——	20
4.	Prasad and saini (1991)	Rectangular duct with thin wires on two sides roughness	$10-20$	0.020-0.033	$5-50\times10^{-3}$	24
5.	**Prasad et al., (2015)**	**Rectangular duct with thin wires on three sides roughness**	**10-40**	**0.01126-0.0279**	$3-20\times10^3$	**23**

Table (2) shows the optimum values of roughness Reynolds number developed by different authors on their respective range of roughness parameters.

CONCLUSIONS

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

For a particular set of values of roughness and flow parameters it has been found that the optimized conditions always correspond to a fixed value of roughness Reynolds number $\left(e^{+}_{opt} = e/D\sqrt{\left(\frac{f_r}{2}\right)}\; Re\right) \approx 23.15$.

Efficiency parameters (B^{-1},C^{-1} & L^{-1}) of three sides roughened solar air heaters for flow and roughness parameters, relative roughness height (e/D),relative roughness pitch (p/e) and flow Reynolds number (Re) have greater values as compare to (Prasad and saini,1991).

For three sides artificially roughened solar air heaters, optimal thermo hydraulic performance conditions have been obtained when roughness height is slightly higher than transition sub-layer thickness (δ').

Relationship between flow parameters and roughness has been presented in the form of performance curves that gives an idea for the selection of these parameters to obtain the optimal thermo hydraulic conditions for three sides artificially roughened solar air heaters.

REFERENCES

1. Dalle Donne. M. and Meyer. L., Turbulent convective heat transfer from rough surfaces with two-dimensional rectangular ribs, Int. J. Heat and Mass Transfer, Vol. 20, pp. 582-620. (1977)
2. Dipprey. D. F. and Sabersky. R. H., Heat and momentum transfer in smooth and rough tubes at various prandtl numbers, Int. J. Heat transfer, Vol. 6, pp. 329-353. (1963)
3. Edwards. F. J. and Sheriff. N., The heat transfer and friction characteristics for forced convection flow over a particular type of rough surface, Int. developments in Heat transfer. Proc. Heat transfer Conf. ASME, pp. 415-425. (1961)
4. Emerson. W. H., Heat transfer in duct in region of separated flow, Proc. Third Int. Heat transfer Conf., Vol. 1, pp. 267-275. (1966)
5. Gupta. D, Solanki. S. C. and Saini J. S., Thermo-hydraulic performance of solar air heaters with
6. roughened absorber plates. Solar Energy. Vol. 61, pp. 33-42. (1997)
7. Han. J.C., Heat transfer and friction channels with two opposite rib-roughened walls, Trans. ASME J. of Heat transfer, Vol. 106, pp. 774-781. (1984)
8. Karwa, R., Solanki. S.C., Saini, J.S., Heat transfer coefficient and friction factor correlation for the transitional flow regime in rib roughened rectangular ducts. Int. J. Heat Mass Transfer, Vol. 42, pp. 1597–1615. (1999)
9. Karmare. S. V. and Tikekar. A. N., Experimental investigation of optimum thermo hydraulic performance of solar air heaters with metal rib grits roughness, Solar Energy, Vol. 83, pp. 6-13. (2008)
10. Kolar. V., Heat transfer in turbulent flow of fluids through smooth rough tubes, Int. J. Heat Mass transfer, Vol. 8, pp. 639-653. (1964)
11. Layek. A., Saini. J. S, and Solanki. S. C., Second law optimization of a solar air heater having chamfered rib–groove roughness on absorber plate, Renewable Energy, Vol. 32, pp. 1967-1980. (2007)
12. Lewis. M. J., An elementary analysis for predicting the momentum and heat transfer characteristics of hydraulically rough surface, Trans. ASME J. of Heat transfer, Vol. 97, pp. 249-254. (1975)
13. Lewis. M. J., Optimizing the thermo hydraulic performance of rough surfaces, Int. J. Heat Mass Transfer, Vol. 18, pp. 1243-1248. (1975)
14. Mittall. M. k. and Varshney. L., Optimal thermo hydraulic performance of a wire mesh Packed solar air heater, Solar Energy, Vol. 80, pp. 1112-1120. (2005)
15. Necati Ozisik. M., Heat transfer-A basic approach. McGraw-Hill, Singapore, pp. 249-253. (1985)
16. Nunner. W., Heat transfer and pressure drop in rough tube, AERE Lib/Trans, Vol. 786, pp. 34-47. (1958)
17. Owen. P. R. and Thomson. W. R., Heat transfer across rough surface, J. Fluid Mech., Vol. 15, pp. 321-334. (1963)
18. Prasad. B. N., Saini, J. S., Effect of artificial roughness on heat transfer and friction factor in a solar air heater, Solar Energy, Vol. 41, pp. 555-560. (1988)
19. Prasad. B. N. and Saini. J.S., Optimal thermo-hydraulic performance of artificially roughened solar air heaters, Sol. Energy, Vol. 47, pp. 91-96. (1991)
20. Prasad. B.N. and Verma. S.K., Investigation for the optimal thermo hydraulic performance of artificially roughened solar air heaters, Renewable Energy, Vol. 20, pp. 19-36. (2000)

21. Prasad. B. N., Thermal performance of artificially roughened solar air heaters, Solar Energy, Vol. 91, pp. 59-67. (2013)
22. Prasad. B. N., Behura. K. Arun. and Prasad. L., Fluid flow and heat transfer analysis for heat transfer enhancement in three sided artificially roughened solar air heater, Solar Energy, Vol. 105, pp. 27-35. (2014)
23. Prasad, B.N., Kumar, Ashwini and Singh, K.D.P., 2015, Optimization of thermo hydraulic performance in three sides artificially roughened solar air heaters, Sol. Energy, 111, 313-319.
24. Prasad. K., Mullick, S.C., Heat transfer characteristics of a solar air heater used for dry purposes, Applied Energy. Vol. 13, pp. 83-85. (1983)
25. Roberson. J. A. and Crowe. C. T., Engineering fluid mechanics, Houghton Miffin Co., Boston, pp. 264. (1975)
26. Rouse. H. and Howe. J. W., Basic mechanics of fluids, Wiley, New York, pp. 136-137. (1953)
27. Rouse. H., Elementary mechanics of fluids, Wiley, New York, pp. 193. (1946)
28. Saini.R.P. and Saini. J.S., Heat transfer and friction factor correlations for artificially roughened duct with expanded metal mesh as roughness element, Int. journal of Heat mass transfer, Vol. 40, pp. 973-986. (1997)
29. Sheriff. N and Gumley. P, Heat transfer and friction properties of surfaces with discrete roughness, Int. J. Heat Mass Transfer, Vol. 9, pp. 1297-1320. (1966)
30. Webb. R.L, Ekert. E.R.G and Goldstein. R.J., Heat transfer and friction in tubes with repeated-rib roughness, Int. J. of Heat and Mass Transfer, Vol. 14, pp. 601-617. (1971)
31. Webb. R. L. and Eckert. E. R. G., Application of rough surfaces to heat exchanger design, Int. J. Heat Mass Transfer, Vol. 15, pp. 1647-1658. (1972)
32. Webber. N. B., Fluid mechanics for civil engineers, E. & F. N. Spon Ltd London, pp. 88. (1965)