

## THERMAL PERFORMANCE CHARACTERISTICS OF ARTIFICIALLY ROUGHENED AND BOOSTED SOLAR AIR HEATERS

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### ABSTRACT

This paper represents the results on data collected under actual outdoor conditions for artificially roughened and smooth solar air heaters with and without booster mirrors. The results show that the effect of boosting of solar radiation is appreciable and consequently, the thermal efficiency of the roughened collectors with booster mirrors increases further over the roughened ones without any further increase in the pressure drop over that in the roughened ones. The values of the collector heat removal factor and collector efficiency factor of roughened solar air heaters with booster mirrors have been found to increase by 12.6% and 11.9% respectively over the roughened ones without booster mirrors and 45.6% and 46.5% respectively over the smooth ones with booster mirrors and 144.1% and 141% respectively over the smooth ones. For a given value of relative roughness height of 0.022 and relative roughness pitch of 15, the value of thermal performance of roughened collector with booster mirror and without booster mirror have been found out to be about 54% and 46% respectively. A maximum of 1.865% of uncertainty in the value of thermal performance have been found. Such solar air heaters are thermally useful quantitatively and qualitatively both.

**KEYWORDS:** Booster mirror, Relative roughness and flow parameters, Collector performance parameters, Collector thermal performance.

### Nomenclature

$A_c$	[m <sup>2</sup> ]	Collector area
$C_p$	[J/kgk]	Specific heat of air at constant pressure
$D$	[m]	hydraulic diameter of solar air heater duct
$e$	[m]	artificial roughness height
$e^+$		roughness Reynolds number,
		$e^+ = \left(\frac{e}{D}\right) Re \sqrt{\frac{f}{2}}$
$e/D$		relative roughness height
$F'$		collector efficiency factor
$F_R$		collector heat removal factor
$F_o$		collector heat removal factor at $t_0$
$\bar{f}$		average friction factor, $(f_s + f_r) / 2$
$f_s$		friction factor in smooth duct
$f_r$		friction factor in rough duct
$G$	[kg/sm <sup>2</sup> ]	air mass flow rate
$I$	[W/m <sup>2</sup> ]	intensity of solar radiation,
$L$	[m]	collector length
$\dot{m}$	[kg/s]	air mass flow rate,
$\bar{Nu}$		average Nusselt number
$Pr$		Prandtl number
$P$	[m]	roughness pitch
$p/e$		relative roughness pitch
$\bar{St}$		average Stanton number
$t_a$	[C]	ambient temperature

$t_i$  [C] air inlet temperature  
 $t_o$  [C] air outlet temperature  
 $U_L$  [W/m<sup>2</sup>K] overall loss coefficient  
 $W$  [m] collector width  
 $\tau\alpha$  transmittance-absorptance product  
 $\eta$  collector efficiency

**Suffix**

S smooth  
 SB smooth with booster mirror  
 R rough  
 RB rough with booster mirror

1. INTRODUCTION

Solar air heaters need to be investigated further for use in a more efficient way, qualitatively and quantitatively both. Performance studies, testing and design procedures for air heating solar collectors have been reported [1-3]. Papers [4-8] represent the use of booster mirrors for elevating temperature in flat plate collectors. Plane booster mirrors [6] and curved mirror [7] has been used. The works [9-12] report more deep inside with regard to design, testing and performance representation methods of solar air heating collectors of air recirculation and without recirculation types.

Solar air heaters are having lower value of thermal performance due to lower value of heat transfer coefficient between the absorber plate and flowing air through it. Enhancement in heat transfer coefficient of solar air heaters has been tried [13-15]. Authors [13-14] have utilized small diameter wires on the air flow side of the absorber plate at varying pitch which produce turbulency in the laminar sub-layer thickness and enhance heat transfer coefficient, resulting in an appreciable enhancement in thermal performance of such solar air heaters compared to the plane ones under the same operating conditions. Correlation was developed the [13] in terms of the geometrical and operating parameters for the average Stanton number for one sided rough and three sided smooth solar air heater duct given under as :

$$\bar{St} = \frac{\bar{f}/2}{\left[1 + \sqrt{\left(\frac{\bar{f}}{2}\right)\{4.5(e^+)^{0.28} Pr^{0.57} - 0.95\left(\frac{\bar{f}}{e}\right)^{0.53}\}}\right]} \quad (1)$$

The optimal value of the roughness Reynolds number ( $e^+$ ) has been analyzed [16] and investigated [17] to be  $e^+_{opt} = 24$ , which results in the maximum heat transfer and the minimum pressure drop. Results [18] in Fig.1, show that the artificially roughened solar air heaters can perform even better at higher intensity of solar radiation and the rate of increase of temperature rise ( $t_o - t_i$ ), is more in roughened solar air heaters than those in smooth ones at higher values of intensity of solar radiation, which leads to higher values of thermal efficiency in the roughened solar air heaters. Intensive works have been carried out in recent years [19-28] who have reported about various types of provisions of artificial roughness on the absorber plates in solar air heaters to improve performance. However, the improvement in performance in such collectors is associated with increase in pumping power required. Review paper [29] gives a comprehensive report of works so far in the area of artificially roughened solar air heaters. From the above recent works, it can be observed that most of the works have dealt with the different roughness geometry and investigation techniques used in artificially roughened solar air heaters to see the effect on heat transfer enhancement and friction factor. Experimental results [14] also give the effect of artificial roughness on heat transfer enhancement in solar air heaters. Use of booster-mirrors for elevating temperature in solar collectors is also available. But, information is required for the effect of boosting of intensity of solar radiation by booster-mirrors on thermal performance in artificially roughened solar air heaters.

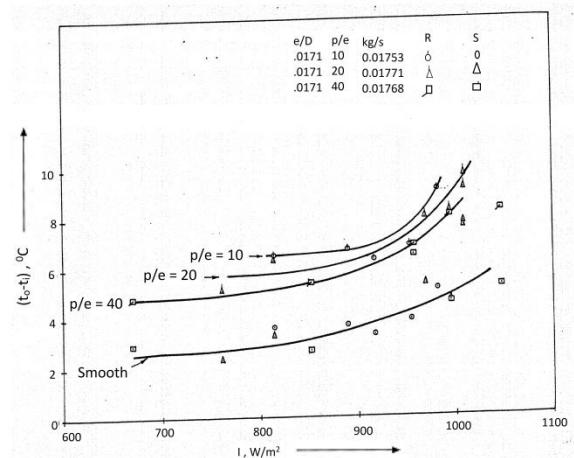


Fig. 1 Air temperature rise as a function of  $p/e$ ,  $e/D$  and  $I$  at almost fixed mass flow rate

Therefore, in the light of the work [18] that artificially roughened solar air heaters can perform even better at higher values of intensity of solar radiation, the present paper, while representing the investigated results [30] to see the effect of boosting of intensity of solar radiation by means of booster mirrors on thermal performance characteristics in the existing artificially roughened solar air heaters, aiming at to enhance thermal performance even further without any additional increase in friction factor which will add more information with regard to artificially roughened solar air heaters with booster-mirrors.

## 2. INVESTIGATION

The experimental set-up as shown in Fig.2 consists of three solar air heater ducts: one smooth and two roughened, each of similar dimensions to that of referred [17]. A wooden sheet of 2.42m length, 0.31m width and 20mm thickness formed the bottom plates of the ducts, the side walls being 25mm thick and 25mm high of 2.42m length to provide an air gap of 25mm between the bottom plate and absorber plate for each of the ducts. Of the total length of 2.42m, only 1.84m happened to be the test length in each duct, remaining 0.58 m including bell-mounted entry length served as the entry length for flow stabilization. Roughness on the absorber plates of the solar air heaters was provided by means of thin wires of varying diameter ( $e$ ), at varying pitch ( $p$ ). The values of the dimensionless parameters, relative roughness pitch, ( $p/e$ ) and relative roughness height, ( $e/D$ ), were found out from the different values of ( $p$ ) and ( $e$ ). The three ducts had separate temperature, pressure and flow measuring devices or sensors which run simultaneously. Provision of booster-mirrors, shown in the figure reflects the solar radiation onto the absorber plates to enhance the intensity of solar radiation. Pyranometer was used to measure the value of intensity of solar radiation. Copper-constantan thermocouples of 28 SWG were used to measure the temperature. Calibrated flange-tap orifice-meters measured the mass flow rates in each ducts. Mass flow rate was controlled by varying

the electric power supply to the blower. Fig.3 shows typically an artificially roughened absorber plate.

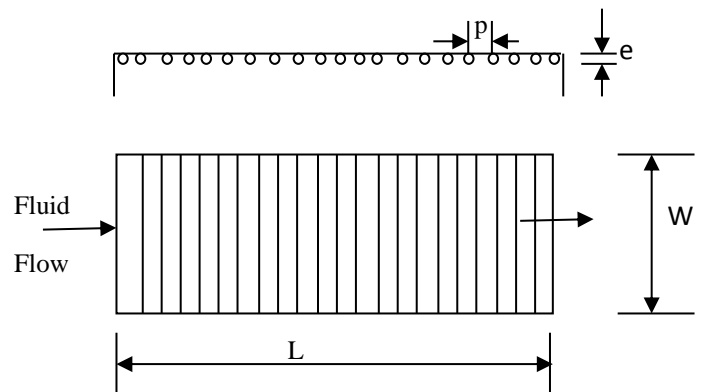
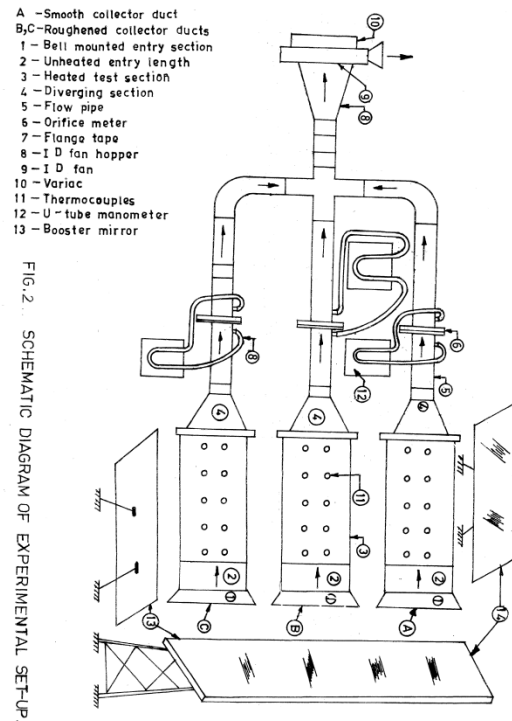


Fig.3 Roughness distribution on absorber plate as a function of  $p$  and  $e$

Data were collected between 10 AM to 2 PM during the months of March to June and November to December. Different values of roughness pitch, roughness diameter and flow rate were taken to yield the values of the roughness and flow parameters,  $p/e$ , in the range of 8 to 40;  $e/D$ , in the range of 0.0112 to 0.0288; mass flow rate, in the range of 0.01576 to

0.0386 kg/s.m<sup>2</sup> and flow Reynolds number, in the range of 8478 to 14686. Altogether in 100 number of test runs, 20 set of roughened solar air heaters with booster mirrors were tested, simultaneously with roughened solar air heaters without booster mirrors and smooth solar air heaters with and without booster mirrors to collect data, which were reduced to obtain the results, and have been represented in the form of various figures.

### 3. RESULTS

Fig.4 shows the effect of boosting of intensity of solar radiation on a particular day. Fig.5 shows the variation of air temperature rise in the solar air heaters typically at varying intensity of solar radiation in roughened collector and roughened collector with booster mirrors at given values of mass flow rate and relative roughness height for varying values of relative roughness pitch of 10 and 15, along with those in smooth ones with and without booster mirrors.

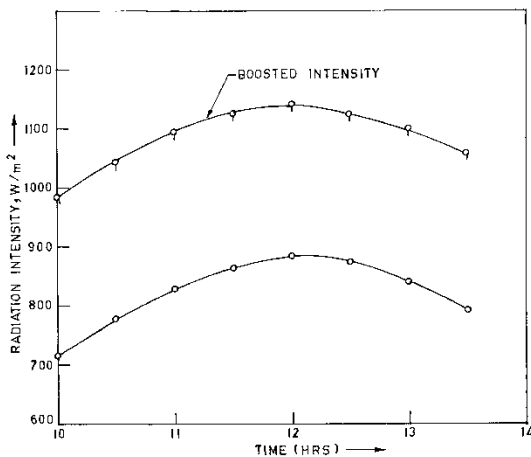


Fig.4 Effect of boosting on intensity of solar radiation

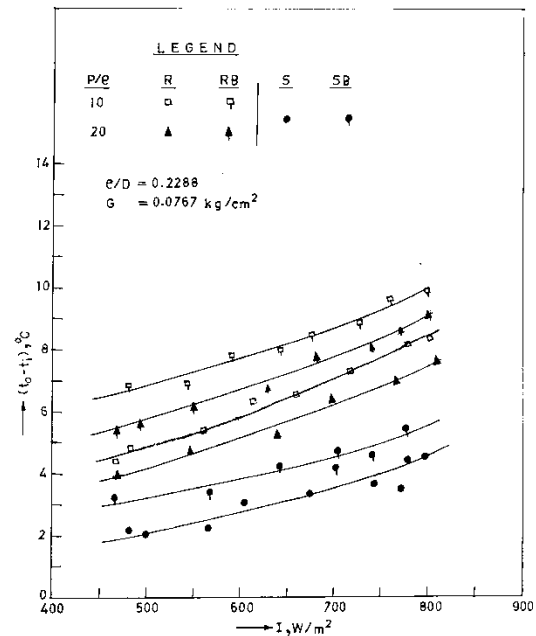


Fig.5 Heat transfer enhancement as a function of  $p/e$  in roughened and boosted solar air heater

Fig. 6 represents the comparison of experimental values of Nusselt number in roughened solar air heater with those of the analytical values [13] for a given value of  $p/e$ , equal to 15 and  $e/D$ , equal to 0.0220. The experimental values of Nusselt number have been worked out by equation (2) and the analytical values have been worked out by equation (3) using equation (1)

$$\overline{Nu} = \frac{hD}{K} \quad (2)$$

$$\overline{Nu} = \overline{St} Re Pr \quad (3)$$

From Fig. 6, it could be seen that the experimental values of the heat transfer data compare well with the analytical values [13] and therefore, the experimental data have been further utilized for working out the values of thermal performance parameters for representation and discussions in the following figures.

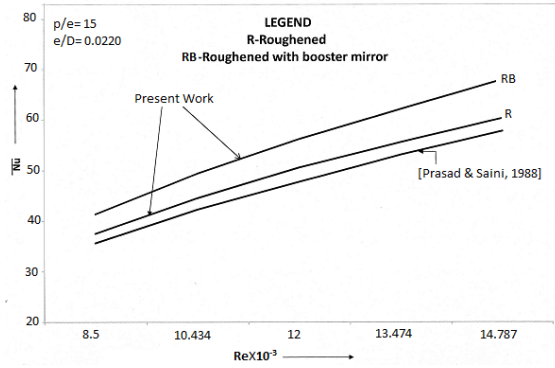


Fig. 6 Comparison heat transfer data.

Since, the performance of solar air heaters is a strong function of mass flow rate, in Figs.7 & 8, each mass flow rate results in an instantaneous efficiency curve for the respective mass flow rate, given by equation (4) as under:

$$\eta = \frac{\dot{m}c_p(t_o - t_i)}{I} \quad (4)$$

The conventional thermal performance equation for the solar collectors is given under as:

$$\eta = F_R U_L \frac{(t_i - t_a)}{I} \quad (5)$$

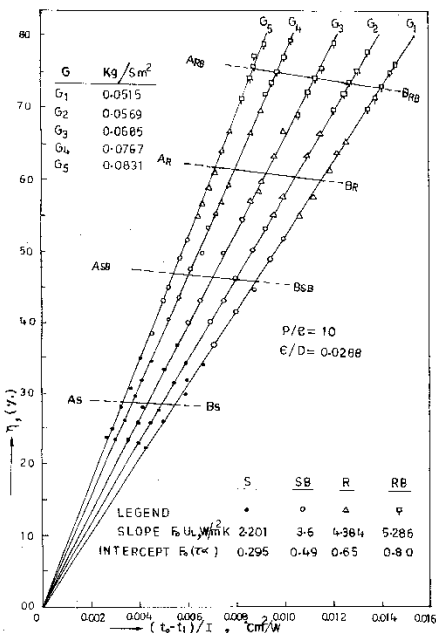


Fig.7 Performance characteristics of solar air heaters

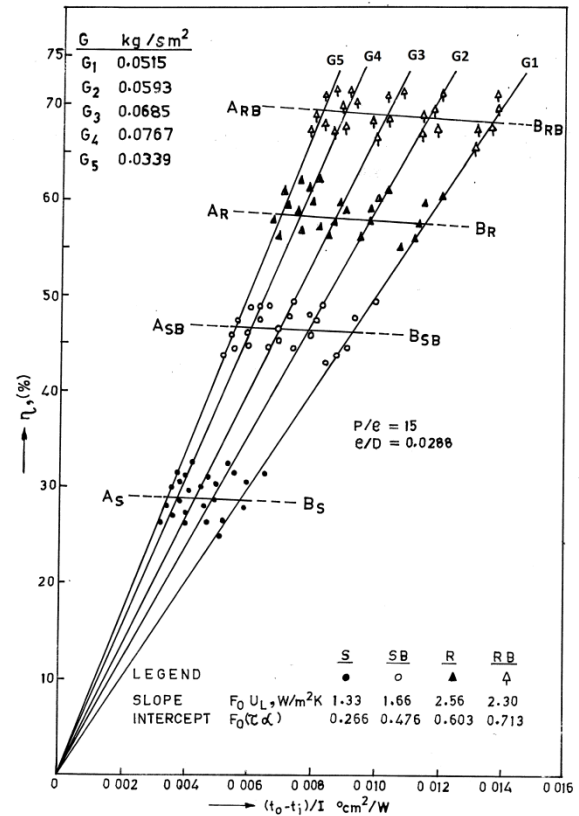


Fig.8 Performance characteristics of solar air heaters

For the solar air heaters, which are generally without recirculation of the air,  $t_i$  is equal to  $t_a$ , and the value of  $(t_i - t_a)/I$  becomes ineffective, because the abscissa value is always zero. Therefore, thermal performance of such solar air heaters has been represented on the basis of outlet air temperature instead of inlet air temperature by the following equation (6), used [9, 11, 12, 14].

$$\eta = F_0(\tau\alpha) - F_0 U_L \frac{(t_i - t_a)}{I} \quad (6)$$

The respective values of the slope  $F_0 U_L$  and intercept  $F_R(\tau\alpha)$ , of the curve represented by Eq. (6), which shows the best fit line to the efficiency data for various mass flow rates, have been obtained and further utilized to work out for the values of the collector performance parameters,  $F_R(\tau\alpha)$  and  $F_R U_L$  from the following equations of reference [Duffie and Beckman, 2006]:

$$F_R(\tau\alpha) = F_0(\tau\alpha) \left[ \frac{\dot{m}C_p/A_c}{\dot{m}C_p/A_c + F_0U_L} \right] \quad (7)$$

$$F_RU_L = F_0U_L \left[ \frac{\dot{m}C_p/A_c}{\dot{m}C_p/A_c + F_0U_L} \right] \quad (8)$$

Fig.9 represents the effect of relative roughness pitch on performance of solar air heaters for a given value of relative roughness height, and Fig.10 represents the effect of relative roughness height on collector performance for a given value of relative roughness pitch.

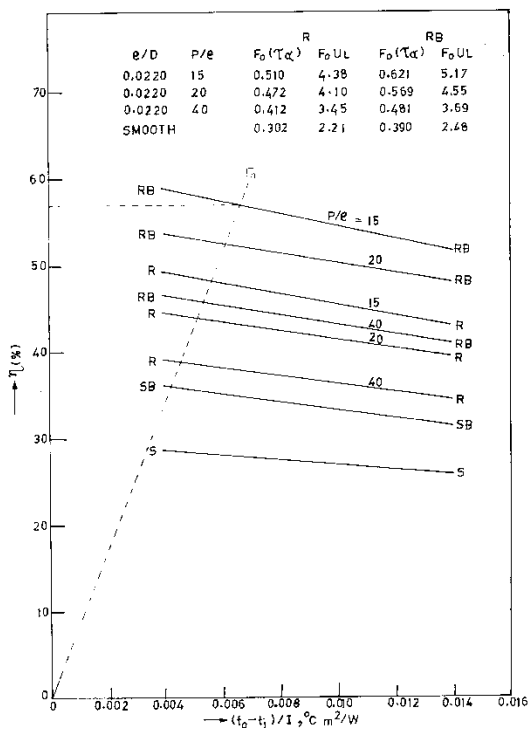


Fig.9 Effect of p/e on performance of solar air heaters

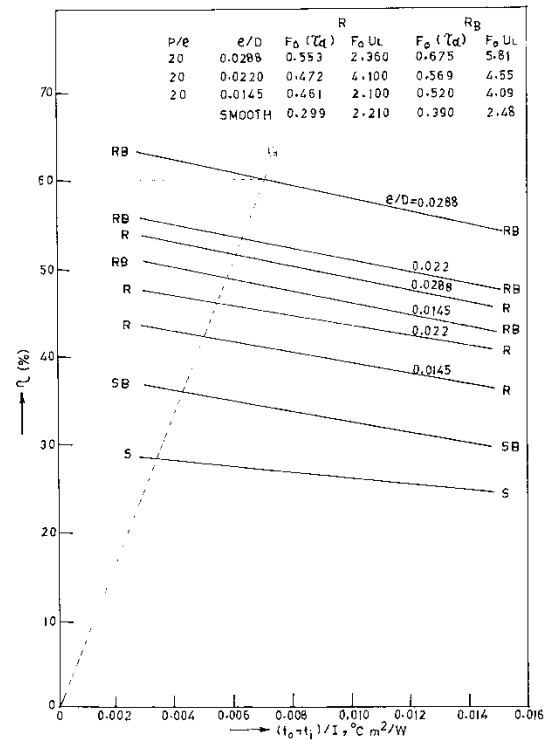


Fig.10 Effect of e/D on performance of solar air heaters

#### 4. DISCUSSIONS ON RESULTS

The effect of boosting of intensity of solar radiation, as could be seen in Fig.4, during the test hours of 10 AM to 2PM on a particular day, remains periodic and is enhanced by about 30% over that of normal radiation.

Variation of temperature rise at varying intensity of solar radiation has been shown in Fig. 5 for both smooth and roughened solar air heaters with and without boosted intensity of solar radiation for a given mass flow rate of 0.0767 kg/sm<sup>2</sup>, relative roughness height of 0.2286 and relative roughness pitches of 10 and 20. The figure indicates that the slope of the curves is more at higher values of intensity of solar radiation. The higher value of the air temperature rise is for roughened solar air heaters with booster-mirrors. Higher value of air temperature rise will result in higher values of thermal efficiency. It could also be seen in this figure that the curve for the roughened collector with boosted solar radiation reflect a bit sharper increase in its slope at higher

values of intensity of solar radiation than those of the curves for the other solar air heaters (roughened and smooth), resulting in higher value of temperature rise in the case of collectors with booster mirrors.

Figs.7 & 8 represent the efficiency data points, the values of which have been worked out by using Eq.(4) ,at varying values of mass flow rate for a given value of relative roughness height of 0.0288 and relative roughness pitch of 10 & 15 respectively. It is clear from these figures that efficiency of the solar air heaters increases with increase in the value of mass flow rate. Its value being higher for the roughened collector with booster mirror, followed by roughened, smooth boosted and smooth ones, at a given mass flow rate. However, its value decreases with increase in the value of relative roughness pitch and increases with the decrease in the value of relative roughness pitch, as could be seen that the value of efficiency data points is more at all mass flow rates for relative roughness pitch value of 10 ( Fig.7) than that of 15 ( Fig.8) . Similar curves for the performance characteristics of solar air heaters could be obtained if the value of relative roughness height is varied for a given value of relative roughness pitch. Increase in the value of efficiency is there for increasing values of relative roughness height.

Curves (straight lines)  $A_{RB}-B_{RB}$  ;  $A_R-B_R$  ; $A_{SB}-B_{SB}$  and  $A_S-B_S$  in Figs.7 &8 show the best- fit lines to the efficiency data for the various solar air heaters for the various mass flow rates , which represent Eq.(6). The values of the slope  $F_oU_L$  and intercept  $F_o(\tau\alpha)$  for the various curves have been found out and mentioned in these figures. Greater value of intercept shows higher value of efficiency, which has been found to be the maximum for the roughened collector with booster mirror, followed by roughened collector without booster mirror, smooth collector with booster mirror and smooth collector without booster mirror.

Figs.9 &10 represent the respective efficiency curves corresponding to Eq. (6), showing the best- fit lines to the efficiency data for the various values of relative roughness pitch equal to 15, 20 and 40, at a given value of relative roughness height of 0.022, and for the various values of relative roughness height of 0.0288, 0.0220 and 0.0145, at a given value of relative roughness pitch of 20. The respective values

of the slope and intercept have been found out for the roughened collectors (with and without booster mirror) together with the smooth ones (with and without booster mirror). It could be seen that thermal efficiency of the roughened collector with booster mirror is more than that of roughened collector without booster mirror. In Fig.9, for a given value of relative roughness pitch of 15 and mass flow rate of G (say), the value of thermal efficiency could be found out to be about 57% in the case of roughened collector with booster mirror, whereas, its value is about 48% for roughened collector without booster mirror, about 36% for smooth collector with booster mirror and about 29% for the smooth collector without booster mirror. Therefore, thermal efficiency has been found to enhance by about 18.75% for the roughened collector with booster mirror over the roughened collector without booster mirror for no extra pumping power(than that in roughened collector without booster mirror), whereas, it is enhanced by about 96% over the smooth ones without booster mirror.

Similarly, the effect of the relative roughness height on efficiency could be seen in Fig.10, which shows that at a given value of relative roughness height of 0.0288 and mass flow rate G (say), thermal efficiency of roughened collector with booster mirror is about 60%, whereas, it is about 51.5% for roughened collector without booster mirror, about 36% for smooth collector with boosting and about 28.5% for the smooth collector without boosting, resulting in about 17% enhancement in thermal efficiency over the roughened collector without booster mirror for the same pumping power required as in roughened collector and about 92% over the smooth ones without booster mirror.

Typically, the values of the slope  $F_oU_L$  and the intercept  $F_o(\tau\alpha)$  taken from Fig.7 have been utilized to work out for the values of the collector performance parameters  $F_RU_L$  and  $F_R(\tau\alpha)$  using Eqs. (6) & (7) to obtain the values of collector heat removal factor  $F_R$  and collector overall loss coefficient  $U_L$ , which have been further utilized to work out for the values of collector efficiency factor  $F_r'$  utilizing equation (9) of Duffie and Beckman [3] written under as:

$$F' = Gc_p \cdot \left[ \ln \left( \frac{F_o U_L}{F_R U_L} \right) / U_L \right] \quad (9)$$

The respective values of  $F_R$ ,  $F'$  and  $U_L$  for the smooth collectors (with and without booster mirror), roughened collectors (with and without booster mirror) are given in Table 1.

Table 1 Respective values of  $F_R$ ,  $F'$  and  $U_L$  in solar air heaters

Parameters	Smooth	Smooth Boosted	Roughened	Roughened Boosted
$F_R$	0.336	0.536	0.728	0.820
$F'$	0.354	0.578	0.845	0.845
$U_L$	6.270	6.100	5.650	5.700

Therefore, it could be seen from Table 1 that the values of collector heat removal factor and plate efficiency factor both are enhanced by using booster mirrors in roughened solar air heaters by about 12.6% and 11.95 respectively for the same pumping power required as that in roughened solar air heaters without booster mirror. The enhancement in the values of collector heat removal factor and plate efficiency factor is about 144% and 141% respectively over the smooth ones without booster mirrors, but at the cost of more pumping power required than that in smooth solar air heaters.

Consequently, the conventional thermal performance equations for the respective solar air heaters, within the range of parameters investigated have been obtained and written as under:

$$\eta_{RB} = 0.82(\tau\alpha) - 4.674(t_i - t_a) / I \quad (10)$$

$$\eta_R = 0.728(\tau\alpha) - 4.113(t_i - t_a) / I \quad (11)$$

$$\eta_{SB} = 0.563(\tau\alpha) - 3.434(t_i - t_a) / I \quad (12)$$

$$\eta_S = 0.336(\tau\alpha) - 2.107(t_i - t_a) / I \quad (13)$$

Eqs. (10) to (13) have been represented by Fig.11 for the comparative view of the conventional thermal performance curves of the respective solar air heaters, which show that thermal performance for the

roughened solar air heaters with booster mirrors have been found to have higher values than the roughened solar heaters.

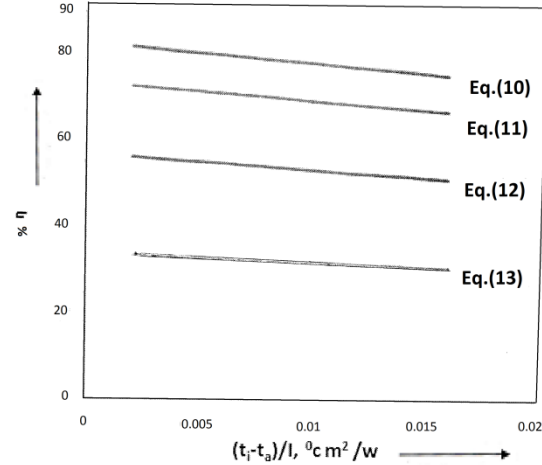


Fig.11 Thermal performance curves for solar air heaters

Error analysis to assert the uncertainty in the values of the results were carried out using the method (Holman, 2011) as given in Appendix B, which shows uncertainty in the values of various parameters and finally 1.865% uncertainty in the value of thermal performance have been found out.

## 5. CONCLUSIONS

Within the range of the parameters investigated, the following conclusions have been derived:

1. Booster mirrors have been found to enhance the intensity of solar radiation by about 30% over the normal radiation.
2. Enhancement of intensity of solar radiation by means of booster mirrors results in enhancement of air temperature rise in solar air heaters.
3. Air temperature rise in solar air heaters depends upon the measure of enhancement in the intensity of solar radiation by means of booster mirrors, mass flow rate of air, value of relative roughness pitch,  $p/e$  and relative roughness height,  $e/D$ . It increases with increase in the value of mass flow rate, increase in the value of intensity of solar radiation, increase in



the value of relative roughness height and decrease in the value of relative roughness pitch.

4. Rate of enhancement in air temperature has been found to be more in roughened solar air heaters with booster mirrors than those of roughened without booster mirror and smooth ones(with and without booster mirror) , resulting in higher value of thermal efficiency .

5. Collector heat removal factor  $F_R$ , and collector efficiency factor  $F'$ , of the roughened collector with booster mirrors have been found to enhance by about 12.6% and 11.9% respectively over the roughened collector without booster mirrors without any extra pressure drop found in the roughened collector, whereas, the values of  $F_R$  and  $F'$  increase by about 144% and 141% respectively over the smooth ones.

6. Artificially roughened solar air heaters with booster mirrors are superior to those of the roughened solar air heaters as well as the smooth ones qualitatively and quantitatively both.

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