International Research Journal of Advanced Engineering and Science
ISSN: 2455-9024

Thermal Performance Characteristics of Three Sides Artificially Roughened Solar Air Heaters With and Without Booster Mirrors

Ashwini Kumar
Department of Mechanical Engineering, National Institute of Technology, Jamshedpur, India-831014

Abstract— *This paper represents the results on data collected under actual outdoor conditions for three sides 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^2] 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, $e^+ = e/D / f/2$ Re
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^2] air mass flow rate
I [W/m^2] intensity of solar radiation,
$\dot{m}$ [kg/s] air mass flow rate,
$\overline{Nu}$ average Nusselt number
Pr Prandtl number
p/e relative roughness pitch
$\overline{St}$ average Stanton number
t_a [C] ambient temperature
t_i [C] air inlet temperature
t_o [C] air outlet temperature
U_L [W/m^{2}K] overall loss coefficient
$\tau\alpha$ transmittance-absorptance product
η collector efficiency

Suffix

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

I. 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 :

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

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 figure 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.

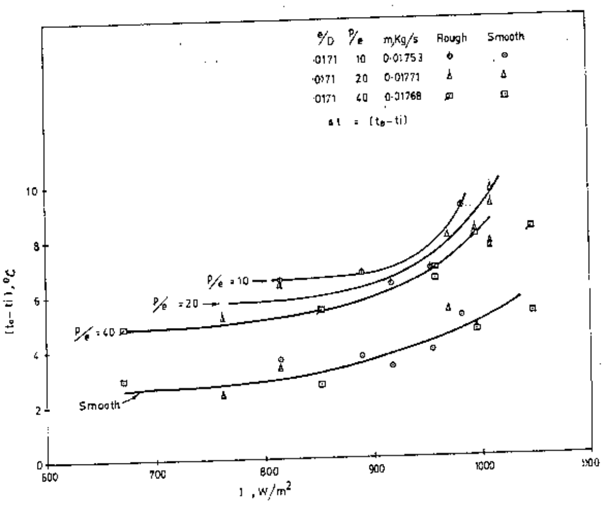
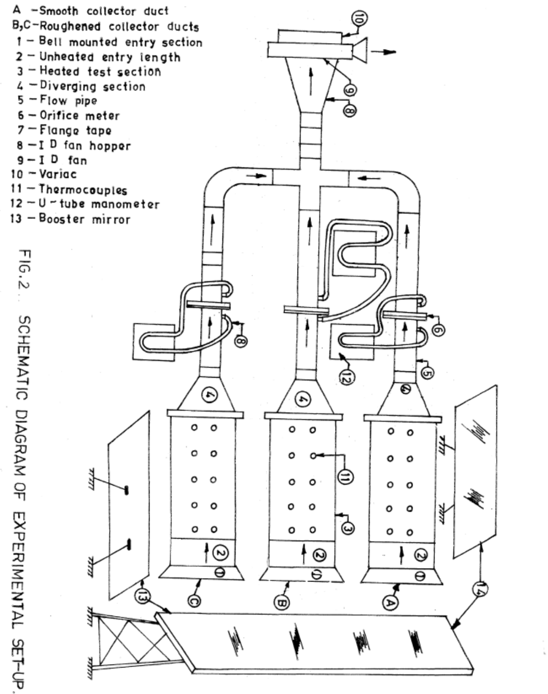


Fig. 1. Air temperature rise as a function of p/e, e/D and I at almost fixed mass flow rate.

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.

II. INVESTIGATION

The experimental set-up as shown in figure 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. Figure 3 shows typically an artificially roughened absorber plate.



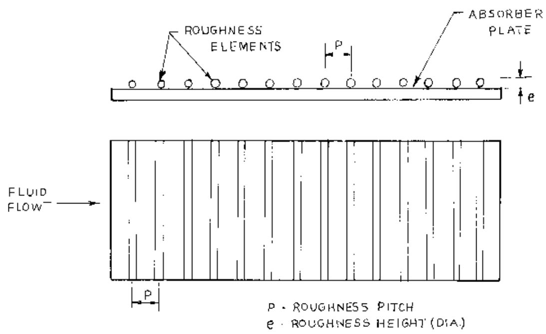


Fig. 3. Roughness distribution on absorber plate as a function of p and e.

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^2 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.

III. Results

Figure 4 shows the effect of boosting of intensity of solar radiation on a particular day. Figure 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.

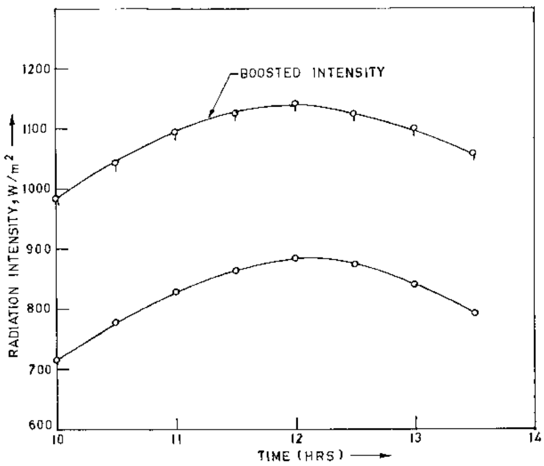


Fig. 4. Effect of boosting on intensity of solar radiation.

Figure 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)

$$\overline{Nu} = \frac{hD}{K} \tag{2}$$

$$\overline{Nu} = \overline{St}\, Re\, Pr \tag{3}$$

From Figure 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.

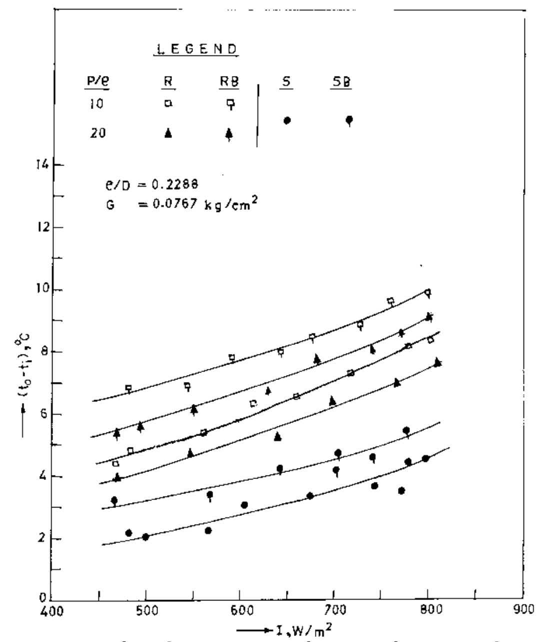


Fig. 5. Heat transfer enhancement as a function of p/e in roughened and boosted solar air heater.

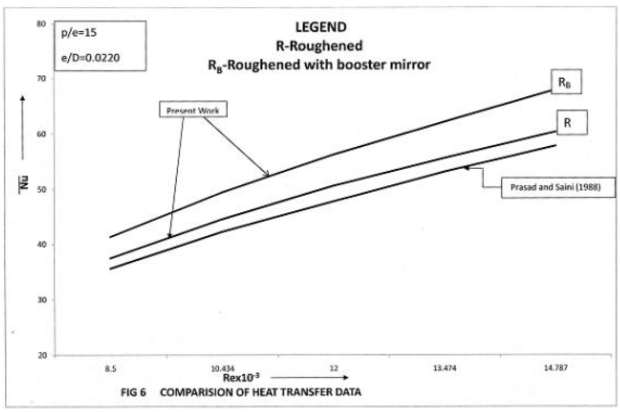


Fig. 6. Comparison heat transfer data.

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

$$\eta = \frac{\dot{m}C_p\,(t_o - t_i)}{I} \tag{4}$$

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

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

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], [1]1, [12], [14].

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

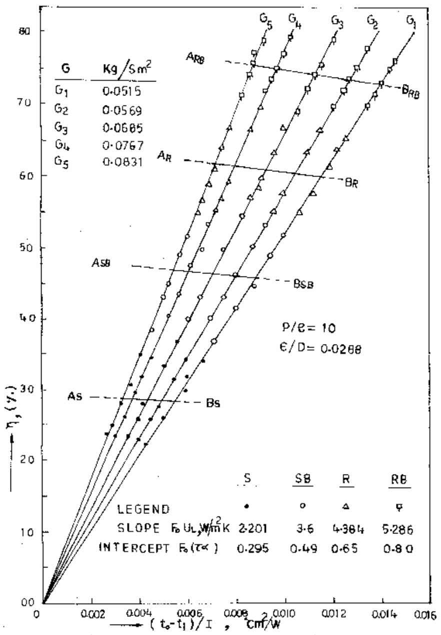


Fig. 7. Performance characteristics of solar air heaters.

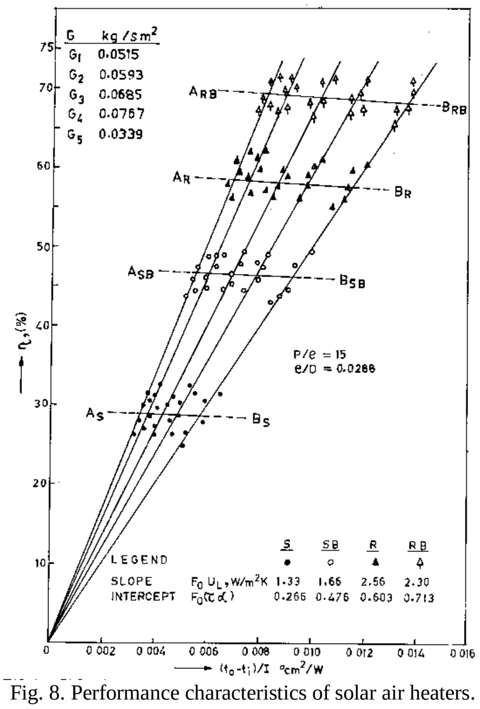


Fig. 8. Performance characteristics of solar air heaters.

The respective values of the slope F_0U_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_RU_L from the following equations of reference (Duffie and Beckman, 2006):

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

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

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

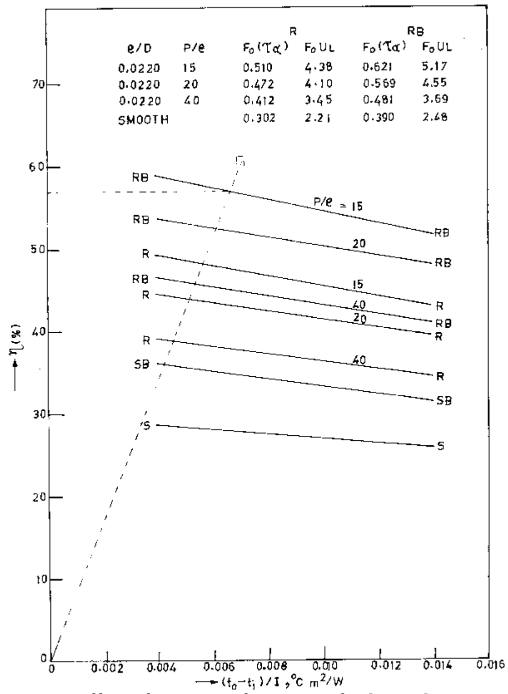


Fig. 9. Effect of p/e on performance of solar air heaters.

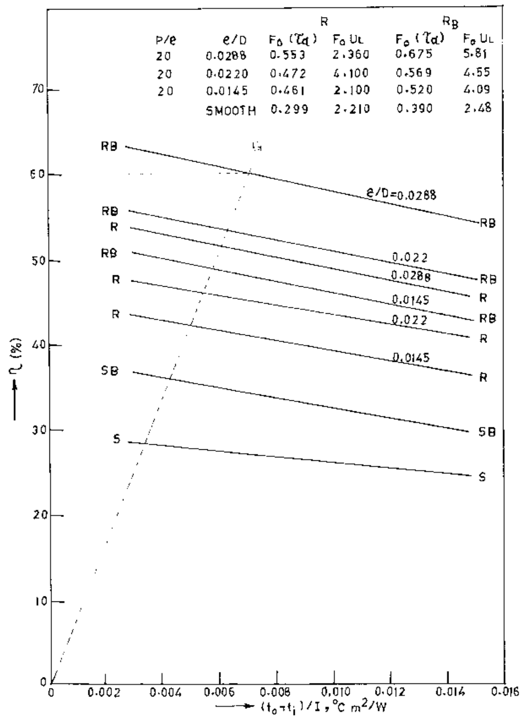


Fig. 10. Effect of e/D on performance of solar air heaters.

International Research Journal of Advanced Engineering and Science
ISSN: 2455-9024

IV. Discussions on Results

The effect of boosting of intensity of solar radiation, as could be seen in figure 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 figure 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^2, 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. Figure 7 & figure 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 (Figure 7) than that of 15 (Figure 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 figure 7 & figure 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.

Figure 9 & figure 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 figure 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 figure 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 figure 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,' utilizing equation (9) of Duffie and Beckman [3] written under as:

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

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 I.

TABLE I. 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 I 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

Ashwini Kumar, "Thermal performance characteristics of three sides artificially roughened solar air heaters with and without booster mirrors," *International Research Journal of Advanced Engineering and Science*, Volume 1, Issue 4, pp. 161-167, 2016.

International Research Journal of Advanced Engineering and Science
ISSN: 2455-9024

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 figure 11 for the comparative view of the conventional thermal performance curves of the respective solar air hearers, 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.

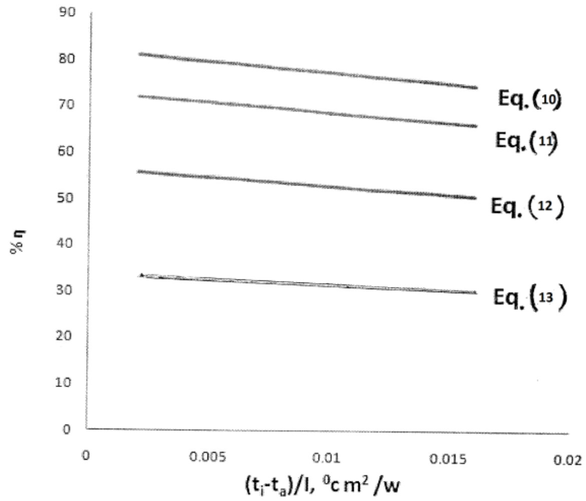


Fig. 11. Thermal performance curves for solar air heaters.

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.

V. CONCLUSION

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.

REFERENCES

[1] C. L. Gupta and H. P. Garg, "Performance studies on solar air heaters," *Sol. Energy*, vol. 11, issue 1, pp. 25-31, 1967.
[2] J. E. Hill, and E. R. Streed, "A method of testing for rating solar air collectors based on thermal performance," *Sol. Energy*, vol. 18, pp. 421-428, 1978.
[3] J. A. Duffie and W. A. Beckman, *Solar Engineering of Thermal Processes*, Wilely Interscience, Newyork, 3rd Edition, 2006.
[4] K. D. Mannan and R. B. Bannerot, "Optimal geometry for one and two faced symmetrical side booster mirror," *Sol. Energy*, vol. 21, pp. 385-391, 1978.
[5] I. A. Sakr and A. I. Hegazi, "Flat plate boosters for elevating temperatures," *Solar Energy International Progress*, vol. 1, pp. 274-297, Pergamon Press, Newyork, 1980.
[6] H. P. Garg and D. S. Hrishikesan, "Enhancement of solar energy on flat plate collector by plane booster mirrors," *Sol. Energy*, vol. 40, pp. 295-307, 1988.
[7] V. Balasubramanian and G. Sankarsubramanian, "Streched tape design of fixed mirror solar concentrator with curved mirror elements," *Sol. Energy*, vol. 51, issue 2, pp. 109-119, 1991.
[8] R. Almanza, F. Munoz, and M. Mazari, "Development of aluminium first surface mirror for solar energy applications," *Sol. Energy*, vol. 48, issue 5, pp. 339-343, 1992.
[9] T. A. Reddy and C. L. Gupta, "Generating application design data for solar air heating systems," *Sol. Energy*, vol. 25, pp. 527-530, 1980.
[10] F. B. Parker, "Derivation of efficiency and loss factors for solar air heaters," *Sol. Energy*, vol. 26, pp. 27-32, 1981.
[11] P. Biondi, L. Cicala, and G. Farina, "Performance analysis of solar air heaters of conventional design," *Sol. Energy*, vol. 41, issue 1, pp. 101-107, 1988.
[12] M. A. Bernier and E. G. Plett, "Thermal performance representation and testing of solar air heating collector," *Trans. ASME*, vol. 110, pp. 74-81, 1988.
[13] B. N. Prasad and J. S. Saini, "Effect of artificial roughness on heat transfer and friction factor in solar air heaters," *Sol. Energy*, vol. 41, issue 1, pp. 555-560, 1988.
[14] B. N. Prasad, "Thermal performance of artificially roughened solar air heaters," *Solar Energy*, vol. 91, pp. 59-67, 2013.
[15] Y.-D. Liu, L. A. Diaz, and N. V. Suryanarayana, "Heat transfer enhancement in air heating flat plate solar collectors," *Trans., ASME, J. Solar Energy Eng*., vol. 106, pp. 358-363, 1984.
[16] B. N. Prasad, and J. S. Saini, "Optimal thermo -hydraulic performance of artificially roughened solar air heaters," *Sol. Energy*, vol. 47, issue 2, pp. 91-96, 1991.

[17] S. K. Verma and B. N. Prasad, "Investigation for the optimal thermo-hydraulic performance of artificially roughened solar air heater," *Renewable Energy*, vol. 20, pp. 19-36, 2000.
[18] B. N. Prasad and J. S. Saini, "Enhancement of solar air heater performance using artificial roughness," *Proc. World Renewable Energy Congress*, U.K., pp. 1067-1071, 1990.
[19] R. Karwa, S. C. Solanki, and J. S. Saini, "Thermo-hydraulic performance of solar air heaters having integral chamfered roughness on absorber plate," *Energy*, vol. 26, pp. 161-176, 2001.
[20] J. L. Bhagoria, J. S. Saini, and S. C. Solanki, "Heat transfer co-efficient and friction factor correlation for rectangular solar air heater duct having transverse wedge shaped rib roughness on absorber plate," *Renewable Energy*, vol. 25, pp. 341-369, 2002.
[21] M. M. Sahu and J. L. Bhagoria, "Augumentation of heat transfer co-efficient by using 90^o broken transverse rib on absorber plate of solar air heater," *Renewable Energy*, vol. 30, pp. 2057-2073, 2005.
[22] A. R. Jaurker, J. S. Saini, and B. K. Gandhi, "Heat transfer and friction characteristics of rectangular solar air heater duct using rib-grooved artificial roughness," *Sol. Energy*, vol. 80, issue 8, pp. 895-907, 2006.
[23] Varun, R. P. Saini, and S. K. Singal, "Investigation on thermal performance of solar air heaters having roughness elements as a combination of inclined and transverse ribs on the absorber plate," *Renewable Energy*, vol. 33, pp. 1398-1405, 2008.
[24] R. P. Saini, and J. Verma, "Heat transfer and friction correlations for a duct having dimple shape artificial roughness for solar air heaters," *Energy*, vol. 33, pp. 1277-1287, 2008.
[25] S. K. Saini, and R. P. Saini, "Development of correlations for Nusselt number and friction factor for solar air heaters with roughened duct having arc-shaped wire as artificial roughness," *Sol. Energy*, vol. 82, pp. 1118-1130, 2008.
[26] V. S. Hans, R. P. Saini, and J. S. Saini, "Performance of artificially roughened solar air heaters–A review," *Renewable and Sustainable Energy Reviews*, vol. 13, pp. 1854-1869, 2009.
[27] M. K. Gupta and S. C. Kaushik, "Performance evaluation solar air heater for various artificial roughness geometries based on energy, effective and exergy efficiencies," *Renewable Energy*, vol. 34, issue 3, pp. 465-476, 2009.
[28] A. Lanjewar, J. L. Bhagoria, and R. M. Sarvia, "Experimental study of augumented heat transfer and friction in solar air heater with different orientations of W-Rib roughness," *Experimental Thermal and Fluid Science*, vol. 35, issue 6, pp. 986-995, 2011.
[29] A. K. Patil, J. S. Saini, and K. Kumar, "A comprehensive review on roughness geometries and investigation techniques used in artificially solar air heaters," *Int. Journal of Renewable Energy Research*, vol. 2, pp. 1-15, 2012.
[30] G. N. Sah, "Thermo-hydraulic effect for fully developed turbulent flow in roughened solar air heaters with booster mirrors," Ph.D. Thesis, Ranchi University, India, 2002.
[31] B. N. Prasad, A. Kumar, and K. D. P. Singh, "Optimization of thermo hydraulic performance in three sides artificially roughened solar air heaters," *Solar Energy*, vol. 111, pp. 313-319, 2015.
[32] A. Kumar, B. N. Prasad, and K. D. P. Singh, "Performance characteristics of three sides glass covered smooth solar air heaters," *Transylvanian Review*, 2016.
[33] A. Kumar, K. D. P. Singh, and B. N. Prasad, "Enhancement of collector performance parameters in three sides artificially roughened solar air heater," *O P Jindal University, Conference Proceedings*, 2016.
[34] A. Kumar and M. Alam, "A review on comparative study of thermal performance of artificially roughened solar air heaters," *Int. Research J of Advanced Engineering and Science*, vol. 1, issue 2, pp. 4-12, 2016.