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Plate Temperature and Heat Transfer Characteristics of Three sides Roughened and Boosted Solar Air Heaters

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***Abstract*— *Higher value of intensity of radiation on absorber plate of solar air heaters and effective heat removal from the plate by the carrier fluid, air, enhances thermal performance of solar air heaters. The paper deals with the experimental results of enhancing the intensity of radiation by means of booster mirrors and that of heat transfer by means of providing artificial roughness on the air flow side of the absorber plate. An enhancement in radiation of about 40% have been found over the normal incident radiation by means of booster mirrors leading to 7% to 15% higher rate of heat collection. The thermal performance parameters FR and F' have been found to increase in the range of 90% to 130% and 92% to 135% respectively in comparison to those of smooth solar air heaters without booster mirrors and in the range of 10% to 15% in comparison to roughened solar air heater without booster mirrors, within the range of the parameters investigated.*

***Keywords*— *Plate temperature; booster mirror; relative roughness pitch (p/ε); relative roughness height (ε/D); collector heat removal factor (FR); plate efficiency factor (F').*

I. Introduction

The paper introduces the results of an artificially roughened and boosted solar air heater, which is better for higher grade and higher rate energy collection, than those of roughened ones [1-6]. Artificially roughened solar air heaters enhance heat transfer rate and consequent increase in pressure drop. Analytical and experimental results are available for thermohydraulic [7-9] and thermal performance [10-12] of solar air heaters. Use of booster mirrors in solar air heater has been reported [13-15]. Flat plate booster mirrors for elevating temperatures have been used [16]. Results of enhancements in solar energy on flat plate collector by plane booster mirrors are available [17]. Review report [18], suggest addition of side mirror increase the amount of solar radiation and yield to operate in a higher temperature range, to maximize the output of fixed flat plate air collector of porous and non-porous type. But use of booster mirror in artificially roughened solar air heater has remained almost unreported. Experimental results [19] show that rate of increase in air temperature is more for increasing values of intensity of solar radiation. In view of the results [19], use of the booster mirrors has been investigated in artificially roughened solar air heaters [20]. Therefore, the results [20], represented with respect to plate temperature heat transfer and thermal performance characteristics of artificially roughened solar air heater might fill the gap in information regarding the effect of booster mirrors in roughened solar air heaters. Such solar air heater have been found to yield better performance without adding further in pressure drop than those of roughened solar air heaters without booster mirrors.

Nomenclature

A_c collector area, [m^2]
C_p specific heat at constant pressure, [J/kgK]
D hydraulic diameter of solar air heater duct, [m]
ε artificial roughness height, [m]
ε/D relative roughness height
F' collector efficiency factor
F_R collector heat removal factor
F_o collector heat removal factor referred to fluid outlet temperature
G mass flow rate per unit collector area, [kg/sm^2]
h heat transfer coefficient between the plate and air, [W/m^2 K]
I intensity of solar radiation, [W/m^2]
$\dot{m}$ mass flow rate of air, [kg/s]
N_u Nusselt number
p artificial roughness pitch, [m]
p/ε relative roughness pitch
T_a ambient temperature, [K]
T_i inlet air temperature, [K]
T_o outlet air temperature, [K]
t_p plate temperature [C]
t_f fluid (air) temperature [C]
U_L overall loss coefficient, [W/m^2 K]
τα Transmittance-absorptance product
η collector efficiency
η_i collector efficiency referred to fluid inlet temperature
η_o collector efficiency referred to fluid outlet temperature

Suffix

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

II. Investigation

The experimental set-up consists of three similar rectangular solar air heater ducts of high aspect ratio, having separate air entry sections. The exit sections are combined together by pipelines to a single air blower. Air mass flow rate, plate and air temperatures, intensity of solar radiation have been measured by mean of flange-tape orifice meters, 26 SWG copper-constantan thermocouples and pyranometer

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respectively. A simple lay-out of the experimental set-up has been shown in Fig. 1.

A typically roughened absorber plate has been shown in Fig. 2. Covering a wide range of the values of roughness and flow parameters to be p/ε = 10-40; ε/D = 0.0145-0.0288; Re = 6000-18000, I = 450-970 W/m^2; $\dot{m}$ = 0.015-0.0473 kg/s, 20 set of roughened absorber plates have been tested to collect data in 100 number of test runs. Data have been collected simultaneously for roughened, roughened and boosted, smooth with and without boosted solar air heaters, under actual outdoor conditions. Three numbers of reflecting glass mirrors (one top and two side mirrors) have been used for boosting of intensity of solar radiation onto the absorber plates of the solar air heaters.

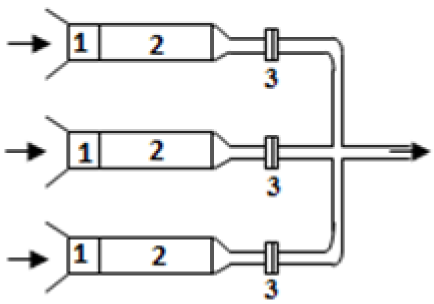

Fig. 1. Layout of experimental set-up.

1. Hydraulic entry length, 2. Test section, 3. Orifice-meter

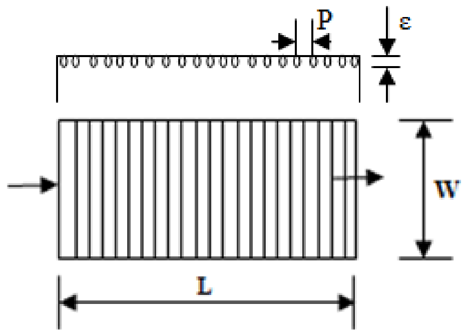

Fig. 2. Absorber plate with artificial roughness.

Small diameter wires have been used as roughness elements. The diameters of the wires are of the order of the viscous sub – layer thickness of hydrodynamic boundary layer under fully developed turbulent flow, so that induced turbulency due to roughness elements doesn't interfere the turbulent core, already existent in the hydrodynamic boundary layer.

III. RESULTS AND DISCUSSIONS

Enhancement in the value of radiation due to boosting on a typical day hours has been shown in Fig. 3. It could be seen from this figure that intensity of radiation falling on the absorber plate increases by an amount of about 40% due to boosting of radiation. Fig. 4 represents the plate temperature distribution in the direction of flow duct length. It could be seen the effect of boosting in solar air heaters in this figure. For example, for a value of X/L=0.50, plate temperature for roughened and boosted solar air heater is about 60^{0}C, for roughened solar air heater it is about 57^{0}C, whereas, it is about 63^{0}C for smooth and boosted solar air heater and that for smooth solar air heater it is about 61^{0}C. Higher values of plate temperature in the case of smooth solar air heaters, is due to the reason that heat removal from the plate is less than that in the roughened solar air heater. Due to boosting effect, plate temperature in roughened and boosted solar air heater is more than that in roughened solar air heater. But it is even less than those in smooth ones. Fig. 5 represents the air temperature distribution, which shows that air temperature is more at every section of the duct length for roughened and boosted solar air heater than those of roughened and smooth solar air heaters. It could also be seen from the slope of the curves in Fig. 5 that the rate of increase of air temperature along the duct length is more for roughened and boosted solar air heater than those of the other solar air heaters. Fig. 4 & 5 represent the plate temperature and air temperature characteristics for the same values of the roughness and flow parameters and intensity of solar radiation.

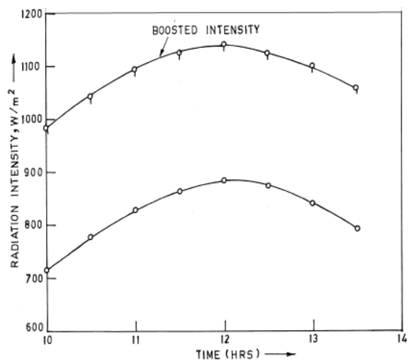

Fig. 3. Effect of boosting on I.

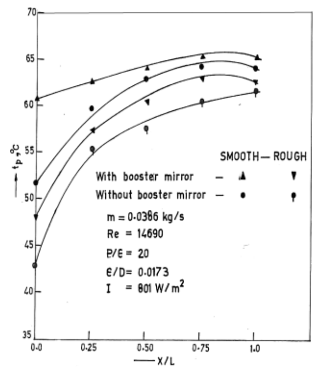

Fig. 4. Plate temperature distribution.

Fig. 6 represents the average values of the plate temperature as well as plate - to - fluid temperature difference in the respective solar air heaters at given values of roughness and flow parameters, as a function of intensity of solar radiation. It could be seen from this figure that due to the effect of boosting, plate temperature in the roughened and boosted solar air heater is more than that in the roughened solar air heater. As also, the plate temperature in smooth and boosted solar air

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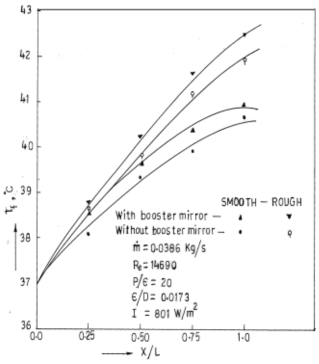

Fig. 5. Air temperature distribution.

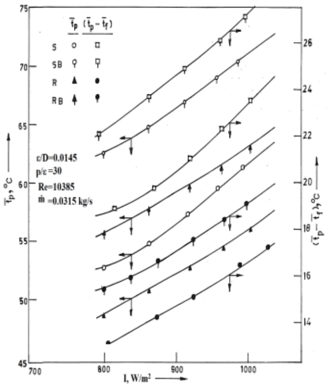

Fig. 6. Effect of I on plate and fluid temperature.

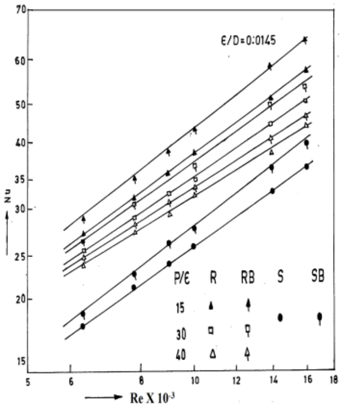

Fig. 7. Effect of p/ϵ on Nu.

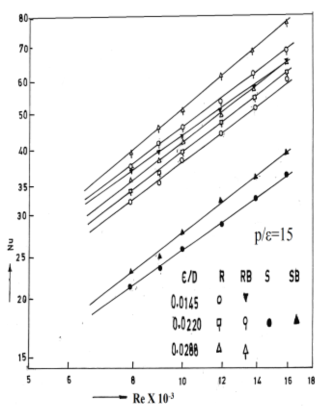

Fig. 8. Effect of ε/D on Nu.

heater is more than that in the smooth solar air heater. More effective or higher rate of heat removal from the plate results in lower value of the plate temperature and smaller value of plate- to- fluid temperature difference ($\bar{t}_p$ - $\bar{t}_f$). Higher value of plate- to- fluid temperature difference in roughened and boosted solar air heater than that in roughened solar air heater is due to boosting of radiation. Higher value of plate- to- fluid temperature difference in smooth solar air heaters is due to lower rate of heat removal from the plate than that in roughened solar air heaters. Higher value of plate temperature also leads to more heat losses from the plate.

Figs. 7 & 8 have been drawn to see the heat transfer characteristics of solar air heaters as a function of flow Reynolds number. The value of the heat transfer parameter, Nusselt number (Nu) has been worked out using Eq. (1) as under:

$$Nu = h(D/k) \quad (1)$$

Fig. 7 shows the effect of relative roughness pitch, p/ε on heat transfer for a given value of relative roughness height, ε/D. The values of Nusselt number have been found to be higher in the case of roughened and boosted solar air heater, as also its value increases with decreasing values of p/ε. Fig. 8 shows the effect of ε/D for a given value of p/ε equal to 15. The values of Nusselt number are more in roughened and boosted solar air heater than those of roughened and smooth solar air heaters. The values of Nusselt numbers have been found to increase with increasing values of ε/D. Within the range of the parameters investigated, correlation for heat transfer parameter, Nusselt number, in roughened solar air heaters has been developed as Eq. (2) under;

$$Nu_R = 0.08497(p/\varepsilon)^{-0.053}(\varepsilon/D)^{0.072}\,\mathrm{Re}^{0.721} \quad (2)$$

which compares well with the correlation developed [8], for roughened solar air heater written under as Eq. (3);

$$Nu = 0.08596(p/\varepsilon)^{-0.054}(\varepsilon/D)^{0.072}\,\mathrm{Re}^{0.723} \quad (3)$$

And, therefore, a correlation has been developed for roughened and boosted solar air heater written under as Eq. (4);

$$Nu = 0.09542(p/\varepsilon)^{-0.054}(\varepsilon/D)^{0.0718}\,\mathrm{Re}^{0.730} \quad (4)$$

which predicts an enhancement of about 12% in heat transfer in case of roughened solar air heaters with booster mirrors as compare to roughened solar air heaters without booster mirrors.

3.1 Thermal Performance Parameters, F_R and F'

Solar air heaters generally use air without recirculation, and therefore, the conventional thermal performance Eq.(5) is modified [20] to be Eq.(6) written respectively as under.

$$n_i = F_R(\tau\alpha) - F_R U_L (T_i - T_a)/I \quad (5)$$

$$n_o = F_o(\tau\alpha) - F_o U_L (T_o - T_i)/I \quad (6)$$

Since, the thermal performance of solar air heaters is very much mass flow rate dependent, each mass flow rate results in an individual efficiency curve drawn from the origin for the respective efficiency data points as shown in Fig. 9 for the solar air heaters based on Eq.(7). Higher mass flow rate results

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in higher value of thermal performance. As shown in Fig. 9, higher value of the slope of the curves for higher value of the mass flow rate result in higher value of thermal performance.

$$\eta = \dot{m} C_p (T_o - T_i) / I A_C \tag{7}$$

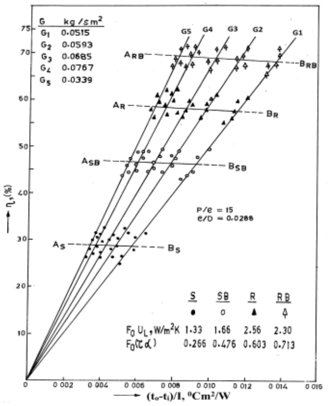

Fig. 9 Thermal performance characteristics.

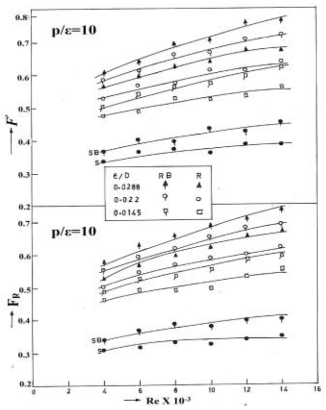

Fig. 10. Effect of ε/D on FR and F'

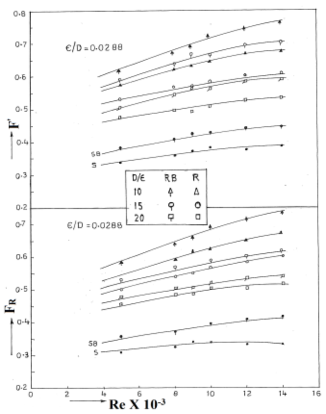

Fig. 11. Effect of p/ε on FR and F.

For solar air heaters without recirculation air inlet temperature T_i is always equal to T_a, and therefore, Eq. (5) becomes irrelevant [12, 22], since abscissa is always zero if, $T_i = T_a$. Therefore, from the experimental values of $F_o U_L$ and $F_o(\tau\alpha)$, as could be seen for the thermal performance characteristics curves in Fig. (9), the values of F_R and F' have been worked out by using the following Eqs. (8) (9) and (10) of references [21, 23]:

$$F_R(\tau\alpha) = F_o(\tau\alpha)\left[(\dot{m} C_p / A_C) / \left\{ (\dot{m} C_p / A_C) + (F_o U_L) \right\} \right] \tag{8}$$

$$F_R U_L = F_o U_L \left[\left\{ \dot{m} C_p / A_C \right\} / \left\{ (\dot{m} C_p / A_C) + (F_o U_L) \right\} \right] \tag{9}$$

$$F' = (\dot{m} C_p / A_C)\left[l_n (F_o U_L / F_R U_L) / U_L \right] \tag{10}$$

Figs. 10 & 11 represent the effect of ε/D and p/ε respectively on the thermal performance parameters F_R and F'. Fig. 10 shows that F_R and F' both increase with increasing values of ε/D. But the rate of increase in the value of F_R and F' both, has been found to be more in roughened and boosted solar air heaters than those in roughened as well as smooth solar air heaters. Similarly, as could be seen in Fig. 10, that the values of F_R and F' increase with decreasing values of p/ε and rate of increase in the values of F_R and F' for roughened and boosted solar air heater is more than those of roughened as well as smooth solar air heaters. The values of F_R and F' have been worked out and found to be more by an amount in the range of 90% to 135% and 10% to 15% in comparison to smooth collectors without booster mirrors and roughened collectors without booster mirrors.

Therefore, the roughened and boosted solar air heaters are superior to the roughened solar air heaters as well as smooth solar air heaters, since they enhance the values of F_R and F' without any further increase in the pressure drop. Roughened and boosted solar air heaters perform better than roughened solar air heater quantitatively and qualitatively both. Such solar air heaters could be very much suitable and useful for space heating of building and other drying processes in agricultural and textile industries for sustainability, as also for the remote areas where electrical power supply is not available.

IV. Conclusion

1. Roughened and boosted solar air heaters are superior to roughened solar air heaters and even more superior to smooth solar air heaters with respect to quality and quantity of energy output both.
2. Correlation for heat transfer parameter Nu, have been developed for roughened and boosted solar air heater, for the range of parameters investigated.
3. The values of collector heat removal factor (F_R) and plate efficiency factor (F') both increase at higher rate with increase in the boosting of solar radiation than those of roughened solar air heaters and smooth solar air heaters and have been found to be more in the range of 90% to 135% in comparison to smooth solar air heaters without booster mirrors and 10% to 15% respectively in comparison to roughened solar air heaters without booster mirrors.
4. Such solar air heaters are useful for space heating of the buildings and low grade energy process industries for sustainability of electrical power.

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