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Analysis of Effect of Heat Transfer and Pressure Drop on Thermohydraulic Performance of Solar Air Heater

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Abstract: *Solar collectors are being used for thermal conversion to raise the temperature of fluid flowing through collector. The principal design factors affecting collector performance are those related to heat loss control and those involving the absorption of solar radiations. Conversion of solar radiations to thermal energy is mainly due to heat transfer coefficient between absorber plate and the fluid flowing in the collector. Convective heat transfer co-efficient between absorber plate and air in a flat plate solar air heater can be enhanced by providing the absorber plate with artificial roughness. The report presents a comparison of effective efficiency and the over all heat/flow performance (HFT) of solar air heaters with different types of artificially roughened surfaces.*

Keywords: *Solar air heater, Artificial roughness, Effective efficiency, HFT, Heat transfer.*

1. INTRODUCTION

Today, per capita energy consumption has got a definite relationship with the standard of living and stage of economic development of the country. The rapid depletion of fossil fuel resources has necessitated an urgent search for alternative energy sources to meet energy demands for the immediate future and generations to come. These range from biomass energy to wind energy and solar energy. Of the many alternatives, solar energy stands out as the brightest long range promise towards meeting the continually increasing demand for energy. Solar energy available freely, omnipresent and indigenous source of energy provides clean and pollution free atmosphere. The simplest and the most efficient way to utilize solar energy is to convert it into thermal energy for heating applications by using solar collectors are water and air. Solar air heaters, because of their inherent simplicity are cheap and most widely used collector devices. The efficiency of flat plate solar air heater is generally low due to low value of convective heat transfer co-efficient between absorber plate and flowing air which increases the absorber plate temperature, leading to higher heat losses. Turbulence promoters or roughness elements on the underside of absorber plates have been used to improve the convective heat transfer by creating turbulence in the flow, however it would result in an increase in friction losses and hence, greater power requirements from a fan or blower. In order to keep the friction losses at a minimum level, the turbulence must be created only in the region very close to the heat transfer surface i.e. in laminar sub layer [6].Taslim and Wadsworth [8] carried out experimental work on heat transfer performance for the case that ribs are mounted on the two opposite roughened surface. However, in the case of solar air heaters, the roughness elements have to be considered only underside of one wall of duct, which receives the solar radiation. Therefore, the solar air heaters are modeled as a rectangular channel having one rough wall and three smooth walls. Based on the literature review, it is found that most of the investigations have been concentrated on the flow Reynolds number in the range of $2000<Re<50000$ for the solar air heaters applications.

2. TYPES OF ARTIFICIAL ROUGHNESS

A most complete study of the effect of roughness on friction and velocity distribution was performed in 1933 by Nikuradse [1] who conducted the now classical series of experiments with pipe roughened by sand grains. Dippery and Sabersky [2] developed a heat transfer momentum analogy for flow in tubes having sand grain roughness. In case of solar air heater, rib type roughness has been investigated mostly. Rib mounted on solid surface prevent development of thermal boundary layer, and increase production of turbulence kinetic energy, and thus enhance turbulent hest transfer. Han and Zhang [7] investigated the effect of broken rib orientation on local heat transfer distributions and pressure drop. Han *et al.* [3] found that ribs inclination at angle of attack 45° result in better heat transfer when compared to transverse ribs. Jia *et al.* [13] investigated that V-shaped rib results in better enhancement in heat transfer in comparison to inclined ribs and transverse ribs. Pavel and Muhammad [11] investigated the effect of porous type roughness on the heat transfer and friction factor. Firth and Meyer [4] used four types of roughness, namely square, helically, trapezoidal and three dimensional surface

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roughness for comparison of heat transfer and friction factor. Jang *et al.* [9] tested two-pass channels with 60° ribs.

3. EFFECT OF ROUGHNESS PARAMETERS ON HEAT TRANSFER AND PRESSURE IN SOLAR AIR HEATER

A number of investigations have been done for roughened duct of solar air heaters. The empirical data used in this comparison are

3.1. Smooth Surface [6]
3.2. Small diameter protrusion wires [5]
3.3. Dimple [12]
3.4. Combination of inclined and transverse ribs [15]

The friction factor and the Nusselt number for a smooth rectangular duct is given by the modifies Blausius equation [6] given below

$$f_s = 0.085\ \mathrm{Re}^{-0.25} \tag{1}$$

$$N_{us} = 0.024\ \mathrm{Re}^{0.8}\ P_r^{0.4} \tag{2}$$

Prasad and Saini [5] investigated heat transfer and friction factor in a solar air heater having small diameter protrusion wires on the absorber plate, of various relative roughness height and relative roughness pitches. Correlations developed for friction factor and heat transfer are

$$f = \frac{(w+2H)f_s + Wf_r}{2(W+H)} \tag{3}$$

where

$$f_r = \frac{2}{\left[0.95\left(P/e\right)^{0.58} + 2.5\log_e\left(\frac{D_H}{2e}\right) - 3.75\right]^2} \tag{4}$$

$$S_t = \frac{f/2}{1+\sqrt{\left(f/2\right)}\left[4.5(e^+)^{0.28}\,p_r^{0.57} - 0.95\left(p/e\right)^{0.53}\right]} \tag{5}$$

$$e^+ = \left(e/D_h\right)\mathrm{Re}\left(f/2\right)^{0.5} \tag{6}$$

$$N_u = S_t P_r Re \tag{7}$$

Burgess and Ligrani [12] developed correlations for dimple roughness are as given below:

$$\frac{N_u}{N_{us}} = 1.0 + 6.83\left(\delta/D\right)^{1.162} \tag{8}$$

When 8850 < Re < 141600

$$\frac{f}{f_s} = 1.0 + A\left(\frac{\mathrm{Re}}{1.77}\right)^B \tag{9}$$

where

$$A = 0.131,\ B = 0.585 \text{ for } \delta/\mathrm{D} = 0.1$$

$$A = 0.220,\ B = 0.585 \text{ for } \delta/\mathrm{D} = 0.2$$

$$A = 0.0038,\ B = 0.537 \text{ for } \delta/\mathrm{D} = 0.3$$

Varun *et al.* [15] developed correlation for Combination of inclined and transverse ribs. Correlations developed for heat transfer and friction factor are

$$N_u = 0.0006 \times \left(p/e\right)^{0.0114} \times (\mathrm{Re})^{1.213} \tag{10}$$

$$f = 1.0858 \times \left(p/e\right)^{0.0114} \times (\mathrm{Re}) - 0.3685 \tag{11}$$

4. THERMO HYDRAULIC PERFORMANCE AND OVER ALL HEAT/FLOW PERFORMANCE (HFT) OF SOLAR AIR HEATER

The artificial roughness has been used extensively for the enhancement of forced convective heat transfer coefficient. It has been found that the artificial roughness applied on heat transferring surface breaks the viscous sub-layer to reduce thermal resistance close to the surface. However, energy for creating turbulent has to come from the fan or the blower and excessive turbulence means excessive power requirement. It is, therefore, necessary to optimize the system to maximize heat transfer while keeping friction losses at the minimum possible level. Therefore the selection of roughness geometry has to be based on effective efficiency. Effective efficiency of solar air heater on the basis of net thermal energy gain is obtained by subtracting the equivalent thermal energy that will be required to overcome the friction power, from the collector useful gain. The effectiveness is given by

$$\eta_e = \frac{q_{u-P_{m/C}}}{IA_c} \tag{12}$$

where C is the conversion efficiency and its typical values of various efficiencies is 0.2. Ridouane and campo [14] proposed a pair of representative ratios for the quantification of the heat transfer efficiency and the pressure drop efficiency, whose ratio gives the overall heat/flow performance (HFP) as below

$$HFT = \frac{E_{HT}}{E_{PD}} \tag{13}$$

where $E_{HT} = \frac{h}{h_s},\ E_{PD} = \frac{\Delta P}{\Delta P_s}$

Suffix‘s’ for smooth absorber plate.

The rate of useful thermal energy gain (q_u) and mechanical power (P_m) consumed, has been obtained by using the following.

$$q_u = F'\left[1(r\alpha) - \frac{U_L(T_0 - T_i)}{2}\right]A_c \tag{14}$$

where $$F' \frac{h}{h+U_L} \tag{15}$$

$$P_m = VA\Delta P \tag{16}$$

$$\delta P = {(2fLV^2\rho)}\Big/{D_H} \tag{17}$$

The values of heat transfer co-efficient h and friction factor f have been determined from correlations developed by several researchers.

5. RESULTS AND DISCUSSIONS

The variation of effective efficiency of the roughened plate solar air heaters has been plotted and compared with those of the smooth duct under similar conditions. Variation of HFT as a function of Reynolds number for different roughness geometries has been also plotted. It has been observed from fig. 1 that effective efficiency increases with increase in mass flow rate i.e. increase in Reynolds number. Fig. 2 and Fig. 4 show the variation of effective efficiency as a function of Reynolds number for various values of e/D_H. Fig. 3 shows the variation of effective efficiency as a function of Reynolds number for various values of δ/D_H. It can be observed from these figures that for given values of roughness parameters, similar trend in variation of effective efficiency is obtained with Reynolds number. Initially effective efficiency increases with the increase of Reynolds number, attains maxima and there after it starts decreasing. The reason may be due to dominance of mechanical power, which is required to overcome the friction losses in the duct. It has been also observed that the effective efficiency corresponding to the higher values of e/D_H is better in the lower range of Reynolds number; however the value of effective efficiency is reversed in the higher range of Reynolds number. Fig. 3 shows that the effective efficiency

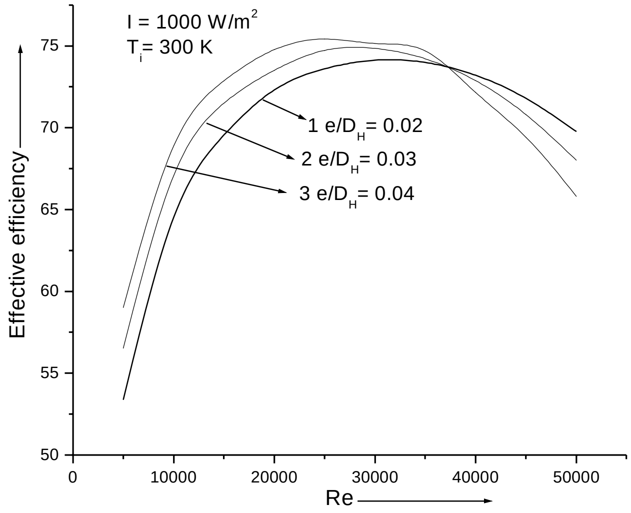

Figure 2: Effective Efficiency vs Reynolds Number [5]

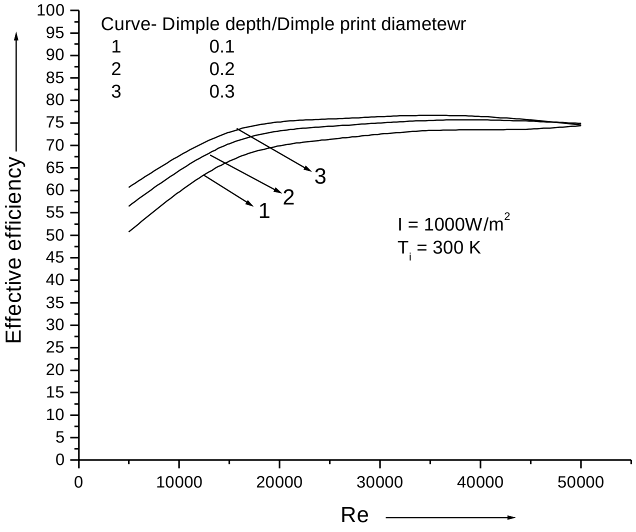

Figure 3: Effective Efficiency vs Reynolds Number [12]

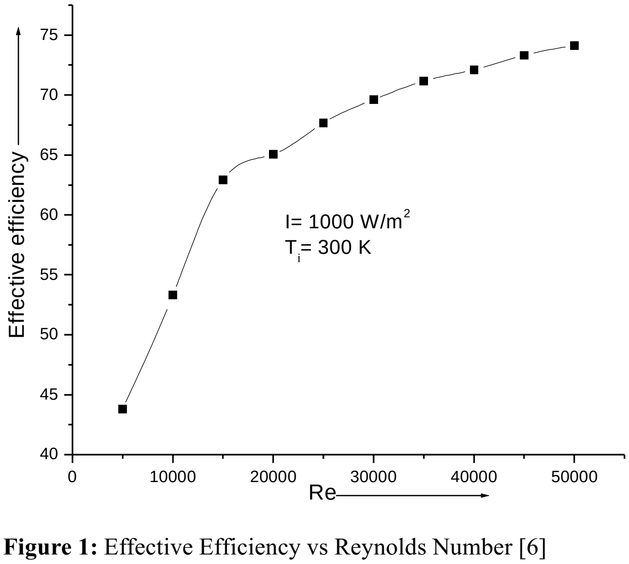

Figure 1: Effective Efficiency vs Reynolds Number [6]

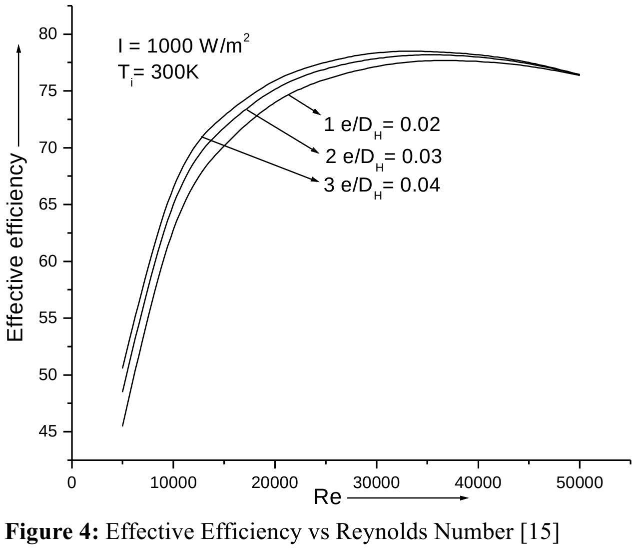

Figure 4: Effective Efficiency vs Reynolds Number [15]

corresponding to the higher values of δ/D_H is better in the higher range of Reynolds number. This is because the deeper dimple increases the intensity of vortices and associated secondary flow ejected from the dimple as well as increases three dimensional turbulence productions.

In case of protrusion wires Fig. 5, it has been observed that HFT decreases with increase in Reynolds number and increase in e/D_H. Fig. 6 shows the HFT increases with increase in δ/D_H and HFT decrease with increase in Reynolds number. But in case of Combination of inclined and transverse ribs HFT increases with increase in Reynolds number as well as increase in e/D_H.

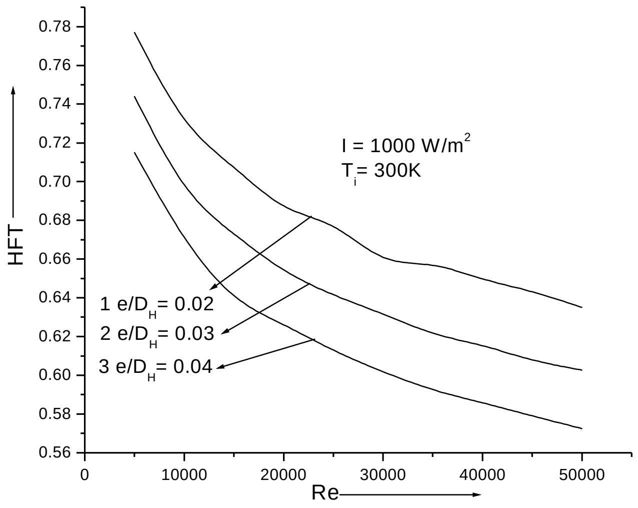

Figure 5: HFT vs Reynolds Number [5]

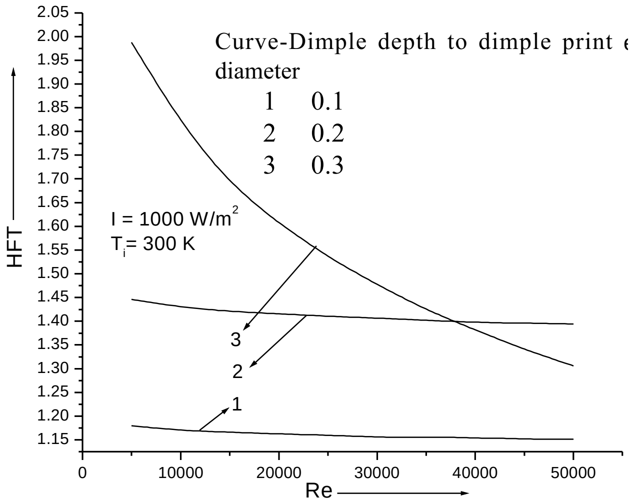

Figure 6: HFT vs Reynolds Number [12]

Table 1
Values of System and Operating Parameters

Parameters	*Values*
Length, L (mm)	1000
Width, W (mm)	411
Height, H (mm)	50.8
Insolation, I (W/m^2)	1000
Over all loss Coefficient, U_L(W/m^2 °C)	5
Transmittance–Absobtance, ($\tau\alpha$)	0.85
Relative roughness height, (e/D_H)	0.02-0.04
Relative roughness Pitch, (P/e)	10
Ratio of dimple depth todimple print diameter, (δ/D_H)	0.1-0.3
Ratio of Channel height to dimple print diameter, (H/D_H)	1
Reynolds Number, (R_e)	5000-50000

6. CONCLUSIONS

It can be concluded from the present analysis that substantial enhancement in the heat transfer can be achieved with little penalty of pressure drop with roughened absorber plate solar air heater. Solar air heater having small diameter protrusion wires as artificial roughness is found to have better effective efficiency and HFT in the lower range of Reynolds number. However in case of dimple, better effective efficiency has been found in the high range of Reynolds number and better HFT has been found in the lower range of Reynolds number. But in case of Combination of inclined and transverse ribs as artificial roughness is found to have better effective efficiency and HFT in the higher range of Reynolds number.

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