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Effect of Solar Insolation and Heat Loss Coefficient on Performance of Solar Air Heater

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Abstract - **This paper presents results of a numerical study of the performance of solar air heaters with Arc shaped rib roughness on the air flow side of the absorber plate. A detailed investigation has been carried out using a mathematical model to study the effects of different levels of overall heat loss coefficient and incidence solar radiation (Solar Insolation) on the thermal efficiency and effective efficiency of air heaters. The study shows that, at air mass flow rates less than about 0.04 kg s^{-1} per m^2 of the absorber plate, roughened duct solar air heaters provide significant performance advantage over the smooth duct air heater. The thermal and effective efficiencies differ only marginally at low flow rates. With the increase in the flow rate, the difference between the thermal and effective efficiencies increases because of the increase in the pumping power.**

Keywords - Solar air heater, Thermal efficiency, Effective efficiency, Reynolds number, Friction factor.

1. INTRODUCTION

Solar energy is very large, inexhaustible source of energy. The power from the sun intercepted by the earth is approximately 1.8 x 1011 MW, which is many thousands of times larger than the present consumption rate on the earth of all commercial energy sources. Thus, in principle, solar energy could supply all the present and future energy needs of the world on a continuing basis and makes it one of the most promising of the unconventional energy sources [Duffie and Beckman, 1980]. The energy from sun received on earth in the form of radiations can be easily collected in the form of heat by the use of either a flat plate collector or a concentrating collector. The main applications of these solar air heaters are space heating, drying and in agriculture process. The efficiency of solar air heaters is less due to the poor thermal conductivity of the air. There are various parameters of the solar air heater like size, shape and surface area which can improve the efficiency when these are designed for optimal conditions. The use of artificial roughness is the one of the effective methods to increase the heat transfer in a solar air heater duct [Dipprey and sabersky, 1963; Han, 1984; Web and Ekkert, 1972; Han and Zhang, 1992; Liou and Hawang, 1993].

There are many ways to provide the artificial roughness to the absorber plate. Mainly the roughness used was of two types irregular roughness like provided by san blasting and secondly the regular roughness which is provided by fixing the extra material on the surface in some particular arrangements. The regular roughness geometries may be classified as rectangular, circular, wedge chamfered and baffles on the basis of shape of the roughness elements. These are also classified as transverse, inclined, V shape z shape U shape, W shape etc. based on the orientation of the element with which these elements are used [Gupta and Kaushik, 2009]. These geometries are investigated by several investigators for different operating and geometry parameters. Momin et al [Momin et. Al., 2002], Varun et al [Varun et. Al. 2008], Singh et al (2011), Lanjewar et al (2011, Jaurker (2006) and Layek et al (2007) used the artificial roughness for solar air heaters and based on experimental data correlations for heat transfer and friction factor were also developed. Muluwork et al. (1998) compared the thermal performance of v-shaped staggered discrete ribs with transverse staggered discrete ribs. Momin et al. (2009) experimentally investigated the effect of geometrical parameters of v-shaped ribs on heat transfer and fluid flow characteristics of rectangular duct of a solar air heater. Karmare and Tikekar (2007) experimentally investigated heat transfer and friction characteristics of a rectangular duct having absorber plate roughened with a defined grid of metal ribs of circular cross-section. Saini and Verma (2008) studied the effect of roughness and operating parameters on heat transfer and friction factor in a roughened duct provided with dimple-shape roughness geometry. Varun et al. (2008) carried out an experimental study on heat transfer and friction characteristics by using a combination of inclined and transverse ribs on the absorber plate of a solar air heater and developed the correlation of Nusselt number and friction factor.

The artificial roughness will also results the increase in the friction factor along with rise in the heat transfer which results the reduction in net heat transfer (useful heat transfer – power required to make the air flow). Hence the performance of solar air heaters must be evaluated both as thermal as well as hydraulic which was proposed by

Cortes and Piacentini (1990) called “effective efficiency (η_{eff})”. In this paper an attempt has been made to analyse a solar air heater to study the effect of solar insolation and heat loss on the thermal and effective efficiency of the solar air heater.

2. PERFORMANCE OF SOLAR AIR HEATER

The solar air heaters are analysed for performance based on the operating parameters and roughness conditions. The main parameters which are used to evaluate the performance are heat transfer (thermal efficiency) and thermo-hydraulic performance (effective efficiency).

2.1 Heat Transfer

The performance of a solar collector can be calculated by considering the energy distribution of incident solar energy (S) into useful energy gain (Q_u) by the solar air heater. The energy lost from the solar air heater to the surroundings by conduction, convection and infrared radiation is represented by U_L i.e. collector total loss coefficient. The useful energy output of a collector having an area A_c is the difference between the absorbed solar radiation and the thermal loss is calculated by using the equation given by Duffie and Beckman (1991).

$$Q_u = A_C[S - U_L(T_o - T_i)] \tag{1}$$

Where T_{pm} is absorber plate mean temperature and T_a is ambient air temperature.

Collector performance can be measured in terms of efficiency called collector efficiency as

$$\eta = \frac{\int Q_u dt}{A_C \int G_T dt} \tag{2}$$

Several investigators carried the experimental studies for the performance study of flat plate collectors. The most commonly used models for the performance of flat plate collectors were developed by Hottel and Woertz (1942) and Hottel and Whillier (1958). The useful energy collected per unit area of collector is given by:

$$Q_u = F_R[I(\tau\alpha) - U_L(T_f - T_a)] \tag{3}$$

Where

F_R is the heat removal factor of the flat plate collector; I is solar Irradiation,
$\tau\alpha$ is absorptance of the collector and T_f is temperature of air in duct

F_R is the ratio of the actual rate of heat transfer to the working fluid to the heat transfer rate assuming that the working fluid temperature in the entire collector is same and given by T_f. Then F_R can be computed as as;

$$F_R = \frac{mC_p}{A_C U_L}\left[1 - Exp\left(-\frac{A_C U_L F'}{mc_p}\right)\right] \tag{4}$$

$$F' = \frac{h}{(h + U_L)} \tag{5}$$

The equation for the thermal efficiency of flat plate collector is represented by:

$$\eta = F_R \left[(\tau\alpha) - U_L \frac{(T_i - T_a)}{I} \right]$$

(6)

2.2 Effective Efficiency

The use of artificial roughness leads to the increase in the friction factor between air and absorber plate. This increase in friction factor significantly increases the pumping power requirements for the air flow and hence decreasing the net heat transfer. Cortes and piacentini (1990) proposed parameter called "effective efficiency (η_{eff})" to count for both the thermal and hydraulic performance of the solar air heaters and expressed it as

$$\eta_{eff} = \left(\frac{Q_u - \frac{P_m}{C}}{IA_c} \right)$$

(7)

Where

Q_u is the useful heat transfer (W); P_m is pumping power (W);
A_c is Area of Absorber Plate (m^2); I is the irradiance (W/m^2) and
C is the conversion efficiency (from mechanical power to thermal power) and is given by

$$C = \eta_F \ \eta_m \ \eta_{tr} \ \eta_{th}$$

(8)

Where

η_F = Efficiency of fan; η_m = Efficiency of electric motor
η_{tr} = Efficiency of electrical transmission and η_{th} = Efficiency of thermal power plant

The rate of useful thermal energy may be obtained from the equation

$$Q_u = F'\left[I(\tau\alpha) - U_L (t_o - t_i)/2\right]A_c$$

(9)

Where

F' is collector efficiency factor; I is irradiation; $(\tau\alpha)$ is transmittance-absorptance product;
U_L is total loss coefficient (W/m^2K); t_o outlet temperature of air,; t_i is the inlet temperature of air and
A_c is the collector area.
From equation (5) we have $F' = \left(\frac{h}{h+U_L}\right)$

Where

h is convective heat transfer coefficient (W/m^2K); also

$$Q_u = mC_p (t_o - t_i)$$

(10)

Where

m is mass flow rate of air (kg/sec),
C_p is the heat capacity of fluid (kJ/kg K)

The mechanical power required for the flow of air is given by

$$P_m = VA\Delta p$$

(11)

Where

P_m is the mechanical energy expenditure for air flow (W); V is the velocity of air flowing (m/Sec);
A is the area of cross-section (m^2) for air flow and Δp is the pressure drop across test section (N/m^2).

$$\Delta p = \left(\frac{2fLV^2\rho}{D_h}\right) \quad (12)$$

Where

f is the friction factor; L is the collector length (m); ρ is the density of air (kg/m^3) and

D_h is the equivalent diameter of the air flow passage (m) and is given by

$$D_h = \frac{2WH}{W+H} \quad (13)$$

Where

W is collector width (m) and H is the depth of duct (m).

3. NUMERICAL CALCULATIONS

Numerical calculations have been carried out to evaluate the thermal efficiency (η_{th}) and effective efficiency (η_{eff}) for a collector configuration, system properties and operating conditions. The thermal behavior of artificially roughened solar air heater with arc shape ribs is calculated similar to that of usual flat plate solar air heater; using the irradiation and the heat losses. Equations (1-13) has been used for the computation of the useful heat gain, Q_u, thermal efficiency (η_{th}), heat transfer coefficient (h_w), pressure loss (Δp), pumping power (P_m) and effective efficiency (η_{eff}).

The model has been solved by following an iterative process in MATLAB 2010 for the heat collection estimate, the iteration was terminated when the successive values of the useful heat transfer differs by less than the 0.01% of the Useful heat transfer. The correlations developed for Nusselt number (Nu) and friction factor (f) by Saini and Saini (2008) were used for the calculation of the useful heat transfer, thermal efficiency and effective efficiency and are given below

$$Nu = 1.047\times10^{-3}Re^{1.3186}\times\left(e/d\right)^{0.3772}\times\left(\alpha/90\right)^{-0.1198} \quad (14)$$

$$f = 1.4408\times10^{-1}Re^{-0.17103}\times\left(e/d\right)^{0.1765}\times\left(\alpha/90\right)^{0.1185} \quad (15)$$

The set of system and operating parameters selected are shown in Table 1 for which thermo-hydraulic behavior has been calculated.

Table 1: Value of system and operating parameters

Parameter	Symbol	Units	Values
Length of duct	L	mm	1500
Width of duct	W	mm	300
Height of duct	H	mm	25
Relative roughness height	e/d	–	0.0422
Relative arc angle	α/90	–	0.333
Irradiance	I	W/m^2	600, 900, 1200
Overall loss coefficient	U_L	W/m^2K	5, 10, 15, 20
Transmittance-absorptance	τα	–	0.85
Air inlet temperature	t_i	K	298
Reynolds number	Re	–	2000-17000

By using the equation (3) useful heat transfer and by using equation (6) thermal efficiency were calculated. Equation (7) was used to calculate the effective efficiency for the solar air heater. The results obtained have been presented and discussed in the next section.

4. RESULTS AND DISCUSSION

Based on the correlations developed by Saini and Saini (2008) for Nusselt number (Nu) and friction factors (f) using arc shaped ribs. These parameters were calculated for the constant values of solar Irradiation (I) and Heat loss coefficient (U_L) assumed as I=600, 900 and 1200 W/m^2 and U_L =5, 10, 15 and 20 W/m^{2}K. Various roughness parameters for given geometry were kept constant at the values suggested by the researchers for optimum performance. Numerical calculations has been made for the heat transfer and friction factor in solar air heater for all the possible combinations of heat loss coefficient (U_L) and solar insolation (I) for the selected level. Then from heat transfer and friction factor thermal and effective efficiency were calculated and are presented and discussed in this section.

Figure 1(a-b-c-d) shows the variation of the thermal efficiency versus Reynolds number for fixed values of roughness parameters (e/d and α/90) for heat loss coefficient (U_L=5, 10, 15 and 20 W/m^{2}K) for different values of solar Insolation (I). It is seen from the figure that for solar insolation value I=1200 W/m^2 performance is maximum at a heat loss level of U_L =5 W/m^{2}K for all Reynolds number values; but at the upper levels of heat loss I=1200 W/m^2 performs better up to Reynolds number value of around 22,000 and beyond which lower levels of solar insolation performs better than I=1200 W/m^2. This is due to the reason that for upper levels of insolation heat losses becomes excessive at higher levels of Reynolds number.

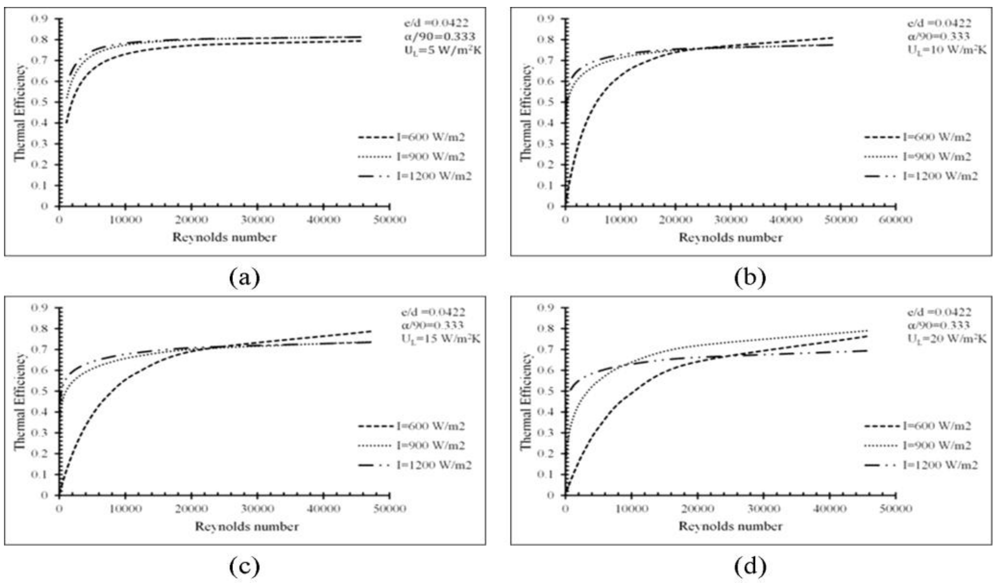

Figure 1: variations of thermal efficiency with Reynolds number at different levels of solar Insolation.

Figure 2 (a-b-c) shows the variation of the thermal efficiency versus Reynolds number for different values of heat loss coefficient at fixed values of e/d and α/90. It is seen from this figure that for all insolation levels heat loss coefficient of 5 W/m^{2}K performs better than all other levels for Reynolds number values of less than 30,000.

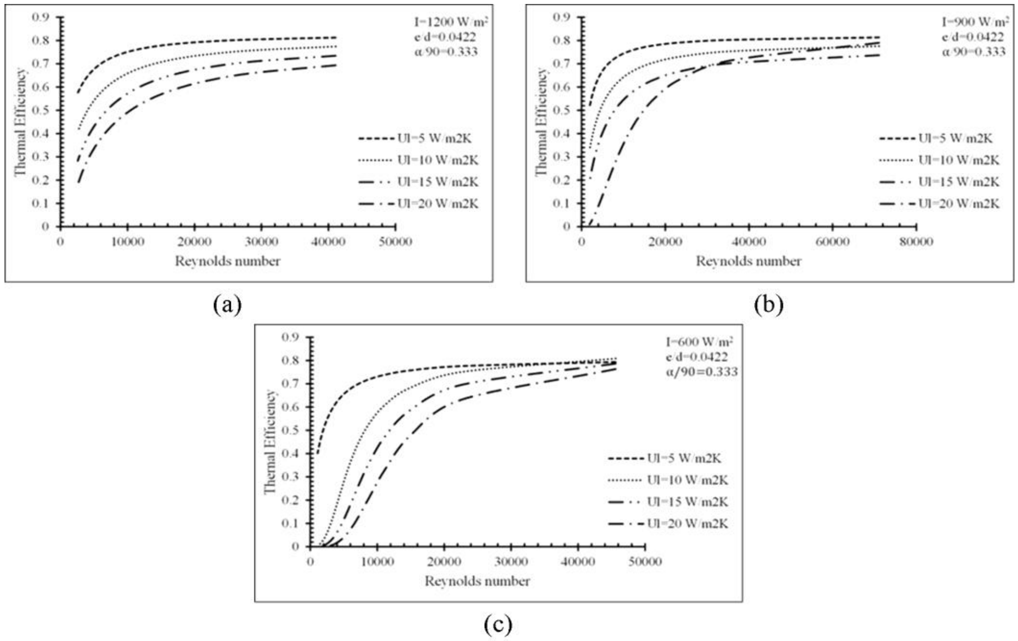

Figure 2: variation of thermal efficiency with Reynolds number at different levels of heat loss coefficient.

The use of artificial roughness leads to the rise in pumping power requirements. The effect of friction factor has been considered and performance is evaluated in terms of effective efficiency of the solar air heater. As the friction factor is only the function of roughness parameters and heat loss coefficient and solar insolation do not have any effect on the friction factor thus the effective efficiency is calculated for heat loss coefficient of 5 W/m^{2}K for different values of Insolation. Figure 3 shows the variation of the effective efficiency with Reynolds number. It is seen from the figure that effective efficiency increases for initial values of Reynolds number less than 8,000 then becomes constant upto 20,000. After the Reynolds number value of 20,000 a decrease was noticed in the effective efficiency. This decrease may be due to the rise in friction factor resulting because of the excessive turbulence of Reynolds number values beyond this range.

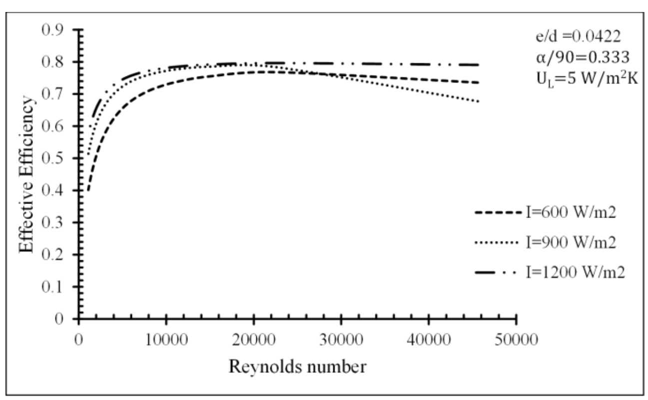

Figure 3: variation of the effective efficiency with Reynolds number.

5. CONCLUSIONS

A numerical study based on the correlations developed for arc shape geometry has been performed to study the heat transfer and friction factor characteristics in terms of thermal and effective efficiency. Based on the results obtained it is concluded that thermal efficiency of solar air heater is maximum for heat loss coefficient value of 5 W/m^{2}K and solar Insolation of 1200 W/m^2. Based on the effective efficiency it may also be concluded that performance for the solar air heater is optimum for the Reynolds number value of 20,000.

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