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THERMO HYDRAULIC PERFORMANCE OF A FORCED CONVECTION SOLAR AIR HEATER USING PIN-FIN ABSORBER SURFACE

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ABSTRACT

The thermo-hydraulic performance of a forced convection solar air heater using pin-fin absorber surface was investigated under the meteorological conditions of Coimbatore city in India. The performance was evaluated during the month of January 2015. The contact area of the absorber plate was increased using pin-fins. Experiments were carried out at optimized air flow rate of 0.05 kg/sec. The energy performance parameters such as, thermal energy absorbed, thermal efficiency of the solar air heater, thermal-hydraulic efficiency of the air heater was evaluated. Temperature of air at the collector outlet was varied between 35^0 C and 65^0 C with an average value of 48^0 C. The thermal efficiency of the solar air heater was about 27% and enhanced optimum efficiency with Pin-fins absorbed plate.

Keywords: Energy Efficiency, Pin-Fins, Solar Air Heater, Thermo-Hydraulic Efficiency

I. INTRODUCTION

Solar air heaters are the special type of heat exchangers used in drying of agricultural materials, space heating and desalination (Kalogirou, 2004). Solar air heaters mainly consist of a thermally insulated absorber plate coated with black paint, one or more glazing plate placed over the absorber by maintaining 25-30 mm gap for air circulation, fan or blower (in the case of forced convection solar air heater (FCSAH)) for circulating the air through the passage and insulated divergent duct at entry and convergent duct at exit. One end of the air heater is connected with the blower and the other end connects to specific applications. The major drawback with conventional solar air heaters is the poor heat transfer between the absorber plate and air due to poor thermodynamic properties of air, which results in poor energy conversion efficiency. Many researchers improved the energy conversion efficiency of a FCSAH using recyclable aluminum cans (Alvarez et al. 2004), obstacles (Esen, 2008), roughened surface absorber plates (Bhushan and Singh, 2010), corrugated absorber plates (Tanda,, 2011), wire mesh (El-khawajah et al., 2011), fins and baffles (Ho et al., 2012) and . A summary of investigations on FCSAH using extended surface absorber plate was also consolidated in a review work reported by Alam et al. (2014). However, the extended surfaces reported in the literature have more pressure drop and more aerodynamic resistance due to the presence of sharp edges (Alam et al. 2014). To overcome these drawbacks, pin-fins were introduced over the absorber plate to reduce the aerodynamic resistance (Nwosu, 2010). The cited literatures confirmed that no major work has been reported with solar air heaters using pin-fin absorber plates. Hence, the main objective of this work is to investigate the energy performance of a FCSAH by using pin-fin absorber plate.

II. MATERIALS AND METHODS

Experimental observations in a FCSAH under the meteorological conditions of Coimbatore (latitude of 11.07^{o}N and longitude of 76.98^{o}E) were made during January 2015 to March 2015.

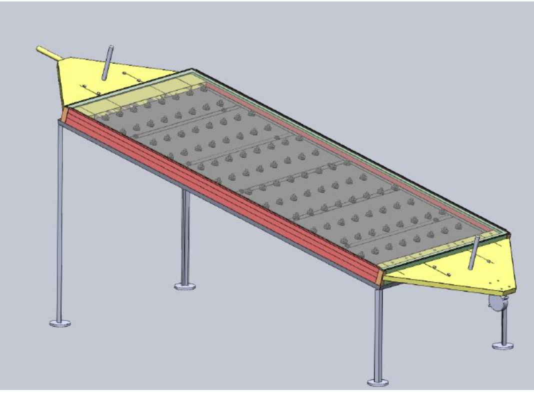

Figure 1 Schematic view of experimental setup

2.1 Solar Air Heater Set Up

A photographic view is shown in Fig. 1. The FCSAH consists of a detachable absorber plate made up of 1.2mm thick mild steel plate attached to aluminum pin-fins of diameter 18 mm and length 24mm. The absorber surface area exposed for tracking of solar radiation is 2m^2 (with dimensions 2m × 1m). Eighty pin-fins were provided over the absorber surface to enhance the exit air temperature. A 5mm thick tempered glass

was placed above the absorber plate to increase the temperature of the air by the greenhouse effect. A 25mm gap was provided between the glass and the absorber surface for air circulation. A cross flow fan with 180W power capacity was fitted at the entry of a FCSAH to force the air through the gap between absorber plate surface and glazing surface. Both sides of the air heater were connected with the help of convergent and divergent air ducts. One side of the air heater was connected to the blower and the other side of the air heater was connected with an orifice-meter and manometer setup. The solar air heater was tilted to an angle about 20^{o} with respect to the horizontal (Shariah et al. 2002). The system was oriented towards face south to maximize the solar radiation incidence on the collector.

2.2 Instrumentation

Six calibrated thermocouples with ±0.5^{o}C accuracy were fixed at different locations (as shown in Fig. 1) of a FCSAH to measure the temperatures at different locations in the absorber plate. Ambient wind velocity was measured with the help of cup type anemometer having ± 0.2m/s. Solar intensity was measured by using solar

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intensity meter with an accuracy of about ±10W/m^2. Ambient relative humidity was measured with the help of sling psychrometer (two thermometers, one covered with wetted wick and another with bare bulb) for measuring wet and dry bulb temperatures. Based on the measured dry and wet bulb temperatures, relative humidity was measured by using psychrometric chart. The instantaneous fan power required for running the blower was measured by Wattmeter. A U tube manometer was attached in the exit air flow path of a solar air heater to measure the air flow rate passing through the solar air heater.

2.3 Experimental Procedure

The experiments in a FCSAH were carried out as per the ASHRAE standard. The air blower was switched ON and air flow rate through the flat plate solar air heater was adjusted to 0.05 kg/s with the help of the control valve (Hegazy, 1999). Before starting experimental observations, the FCSAH was warmed up one hour to avoid initial transients. During experiments, solar intensity and temperature at typical locations (shown in Fig. 1) were measured by using solar intensity meter and thermocouples, respectively. Similarly the wind velocity and ambient relative humidity were observed by using a cup type anemometer and sling pychrometer, respectively. All the experimental observations were made at one-hour interval between 9.00 am to 5.00 pm. Experiments were conducted for ten days continuously and the average value was considered for discussion.

III. THERMODYNAMIC ANALYSIS

A thermodynamic analysis based first and second law of thermodynamics has been used to analyze the energy performance of a forced convection solar air heater working with pin-fins. For steady state flow processes, three equations such as mass, energy balance equations were used to find out the amount of heat input.

3.1 Energy analysis

The mass balance equation can be expressed in the form as

$$\sum m_{in} = \sum m_{out} \tag{3.1}$$

If the effects due to the kinetic and potential energy changes are neglected, the general energy can be expressed in the form as given below:

$$\sum E_{in} = \sum E_{out} \tag{3.2}$$

$$\sum EX_{in} - \sum EX_{out} = \sum EX_{dest} \tag{3.3}$$

The transmitted solar radiation from the transparent glass cover is absorbed by the absorbing plate. The air flows above the absorber plate where it is heated along its path. In order to write the energy balance equations for the systems, the following assumptions are made:

(i) The heat transfer capacities of the glass cover, absorbing plate and insulation are negligible.

(ii) There is no temperature gradient across the thickness of the glass cover and the storage material has an average temperature $T_{st}(t)$ at a time t. This assumption may be achieved by keeping a small thickness of 100 mm storage material.

(iii) The system is perfectly insulated and there is no air leakage from the collector.

(iv) No stratification exists perpendicular to the air flow.

(v) The absorptivity of air is negligible.

3.1.1 Heat output capacity

The amount of heat extracted by a solar air heater is calculated by the following relation:

$$Q_{abs} = m \times c_p \times (T_{out} - T_{in}) \qquad (3.5)$$

3.1.2 Thermal efficiency of a solar air heater

The thermal performance of any type of solar thermal collector can be evaluated by an energy balance that determines the portion of the incoming radiation delivered as useful energy to the working fluid. Thermal efficiency of the solar air heater was estimated using the equation 4 as reported by (Shanmugam and Natarajan, 2006).

$$\eta_{th} = \frac{m \times c_p \times (T_{out} - T_{in})}{A_c \times I} \times 100 \qquad (3.4)$$

where η_{th} drier thermal efficiency, m_a is the flow rate of air through the collector, T_o and T_i are the outlet and inlet air temperatures respectively.

3.2 Exergy analysis

Exergy analysis provides a method to evaluate the maximum work extractable from a substance relative to ambient as reference state (dead state). Exergy analysis has been widely used to optimize the thermal energy systems and also to identify the inefficient components in the system.

$$(1 - \frac{T_a}{T_s})q_u - \dot{m}[(h_{out} - h_{in}) - T_a(S_{out} - S_{in})] = Ex_{dest} \qquad (3.5)$$

3.2.1 General relations

Exergy is an expression for accounting the loss of available energy due to entropy generation in the irreversible systems or processes. An exergy analysis has widely used in design, performance evaluation and simulation of energy systems. The exergy destruction in a system is determined by multiplying the ambient temperature by the entropy increase. The exergy balance can be expressed as by the following equation [63].

$$\sum Ex_{dest} = \sum Ex_{in} - \sum Ex_{out} \qquad (3.6)$$

The total exergy of a system can be divided into four components namely

(i) physical exergy,

(ii) kinetic exergy,

(iii) potential exergy

(iv) chemical exergy

$Ex = Ex^{PH} + Ex^{KN} + Ex^{PT} + Ex^{CH}$ (3.7) Physical exergy is the major part of the exergy at different locations in solar assisted heat pumps. It is defined as the work obtained when the working fluid is brought from the reference conditions to the ambient condition. Physical exergy is given by following equation.

$$Ex_{phy} = [F(\sum X_i h_i^F - T_0 \sum X_i s_i^F) + G(\sum X_i h_i^G - T_0 \sum X_i s_i^G)] \quad (3.8)$$

Where h is the enthalpy, s is the entropy and X is the molar ratio of each component, F refers to the liquid phase, where as G refers to the vapour phase. The other exergy terms were neglected in this work.

The assumptions made in this study are:

- Steady flow operation.
- The effects of potential and kinetic energy are negligible.
- There is no chemical or nuclear reaction.
- Air is treated as an ideal gas with a constant specific heat and its humidity content is ignored.
- The directions of heat transfer to the system and work transfer from the system are positive.

The general exergy balance can be expressed as follows:

$$\sum\left(1-\frac{T_a}{T_s}\right)q_u - W + \sum m_{in}\psi_{in} - \sum m_{out}\psi_{out} = EX_{dest} \quad (3.9)$$

Where, Ψ_{in} and Ψ_{out} are specific exergy (kJ/kg)

$$\Psi_{in}=(h_{in}-h_a)-T_a(S_{in}-S_a) \quad (3.10)$$

$$\Psi_{out}= (h_{out}-h_a)-T_a (S_{out}-S_a) \quad (3.11)$$

3.2.2 Exergy destruction

The changes in the enthalpy and the entropy of the air at the collector are expressed by

$$\Delta h = h_{out} - h_{in} = C_p\left(T_{f,out} - T_{f,in}\right) \quad (3.12)$$

$$\Delta s = s_{out} - s_{in} = C_p In\frac{T_{f,out}}{T_{f,in}} - RIn\frac{P_{out}}{P_{in}} \quad (3.13)$$

The exergy efficiency of a solar collector system can be calculated in terms of the net output exergy of the system or exergy destructions in the system. The irreversibility Ex_{dest} can also be determined by:

$$Ex_{dest} = T_a S_{gen} \quad (3.14)$$

3.2.3 Exergy efficiency

The exergy efficiency of SAH system has been evaluated in terms of the net output exergy of the system. The second law efficiency is calculated as follows:

$$\eta_{II} = 1 - \frac{T_a S_{gem}}{\left(1 - \frac{T_a}{T_s}\right) q_u} \qquad (3.15)$$

3.3 Uncertainty Analysis

Uncertainties of the calculated parameters are estimated according to Holman [29]. In the present work, pressures, temperature, solar radiation, power consumption, velocity and mass flow rate were measured with instruments as mentioned in the previous section. The uncertainty arising in calculating a result due to several independent variables is given by equation (3.16)

$$w_r = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \dots\dots\dots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2} \qquad (3.16)$$

Here R is a given function, w_r is the total uncertainty, x_1 x_2.....x_n is the independent variables, w_1, w_2...w_n is the uncertainty in the independent variables. The total uncertainties for the calculated parameters of heating capacity and thermal efficiency are calculated as 5% and 8%, respectively.

IV. RESULTS AND DISCUSSION

The experiments were carried out under metrological conditions of Coimbatore during the months of January and March 2015. Experiments were carried out continuously during potential sunshine hours (sunshine more than 200 W/m^2). The following data were observed during experimentation. More number of data observations has been made to have realistic comparison among the different modes.

4.1 Temperature at Typical Locations

Temperatures at different locations in a forced convection solar air heater without pin-fins are depicted in Table 1. From Table 1 it is observed that inlet air temperature varies between 28 and 34^{o}C with an average temperature of 31^{o}C. Similarly the temperature at the outlet of air heater is varying between 32^{o}C and 58^{o}C with an average temperature of about 43^{o}C. The absorber temperature is varying between 34^{o}C to 62^{o}C with an average temperature of 47^{o}C.

Similarly, the temperature was measured by replacing the absorber plate with pin-fin integrated absorber plate. Measured temperatures at different locations in a forced convection solar air heater are plotted in Table 1. From Table 1 it is observed that inlet air temperature varies between 28 and 35^{o}C with an average temperature of 31^{o}C. Similarly the temperature at the outlet of air heater is varying between 33^{o}C and 62^{o}C with an average temperature of about 46^{o}C. The absorber temperature is varying between 41^{o}C to 68^{o}C with an average temperature of 54^{o}C. The absorber plate temperature with pin-fins was observed to higher than that of absorber plate without pin-fins due to increased heat transfer area.

4.2 Variation of Solar Intensity

Similarly, the hourly variation of solar intensity during experimentation of solar air heater with pin-fins is depicted in Table 1. From Table 1 it is observed that solar intensity is increasing gradually from 9 am and reach its maximum value of about 750W/m^2 in the noon and reduces to 200 W/m^2 during 5pm. The average value of solar intensity is around 410 W/m^2. Since the solar intensity is the main parameter influencing the performance of the solar air heater.

4.3 Optimization of Air Flow Rate

The mass flow rate of air passing through the solar air heater integrated with pin-fins is to be optimized to improve the thermal efficiency of a solar air heater. The air flow rate through the collector is changed as 0.02 kg/s/m^2, 0.025 kg/s/m^2 and 0.03 kg/s/m^2 by using voltage regulator. The mass flow rate of air was measured by using orifice meter setup fitted with manometer. The temperature variations and thermal efficiency of solar air heater with reference to mass flow rate during peak sunshine hours (700 W/m^2) are depicted in Table 1 and Table 1.

From Table 1, it is understood that maximum outlet temperature was observed for the mass flow

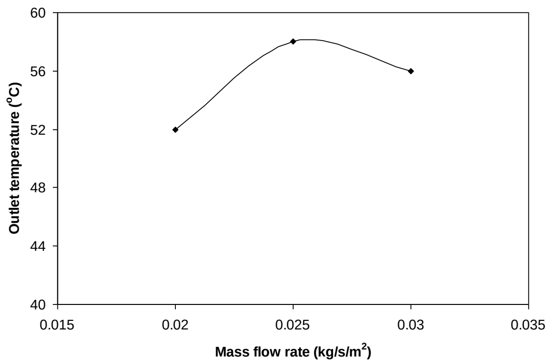

Figure 5.1 Variation of outlet air temperature with air flow rate

ate of 0.025 kg/sm^2.Similarly, maximum thermal efficiency was observed for the mass flow rate of 0.025 kg/sm^2. Hence, the mass flow rate of air recommended for forced convection solar air heaters is around 0.025kg/sm^2.

4.4 Thermal Efficiency of a Solar Air Heater Thermal efficiency of a forced convection solar air heater was evaluated for a constant mass flow rate of 0.025 kg/s/m^2. The thermal efficiency of a forced convection solar air heater integrated with pin-fins is more when compared to the forced convection solar air heater without pin-fins. From the experimental observations with pin-fins, it confirmed that pin-fins can increase the heat transfer area, there by improved the thermal efficiency of the solar air heater. The efficiency of a forced convection solar air heater without pin-fins is varied between 25% and 35%. But the efficiency of a forced convection solar air heater is varied between 41 and 48%. The efficiency of the

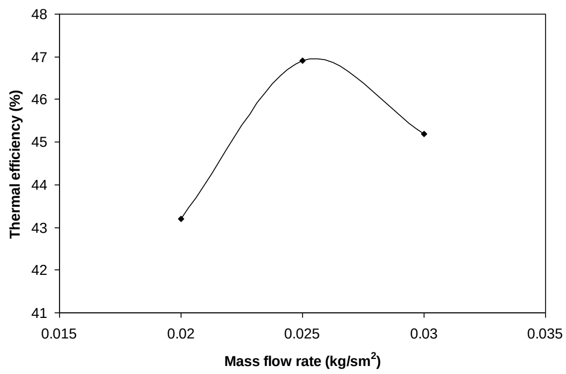

Figure 5.2 Variation of thermal efficiency with air flow rate

forced convection solar air heater integrated with pin-fins enhance the performance of about 20%.

V. CONCLUSION

The exergy efficiency of a forced convection solar air heater working under different ambient conditions using pin-fin absorber plate is depicted in the following figure. From Table 1, it is observed that more exergy efficiency occurs during higher peak sunshine hours. More amount of energy is wasted during peak sunshine hours. The range of exergy efficiency was observed to be similar to previously reported studies.

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