TECHNO-ECONOMIC ANALYSIS OF A SOLAR AIR HEATER WITH DIMPLE SHAPED PROTRUSIONS ON THE SURFACE

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Abstract
In the present article, the techno-economic evaluation has been carried out for solar air heater (SAH) with dimple shaped protrusions on the absorber of the heater. The objective of the present experimental study is to make energy efficient and cost effective SAH. All the experiments to evaluate the thermal performance of the SAH have been conducted in Moradabad (India) on forced convection. The system was fabricated with locally available materials for a reasonable rate. The simple solar economics have been taken into account for the initial investments. Results shows that the thermal efficiency of the system was found around 46.11% while the overall heat loss coefficient was 8.71 W/m^2 ^{o}C and payback period of the system was estimated around 4.41 years.
Keywords: solar energy, air heater, economics, performance, payback period

1. Introduction

In recent years, numerous investigations have been carried out for thermal performance evaluation of different designs of solar air heaters or air collectors. Tests were carried out also for modifications or design optimizations of existing designs. The researchers or scientists paid attention not only the designs of the systems but for adequate processing also. Various types of ducts, flow passages or channels, solar collectors, fluid flow characteristics and modification in glazing were the major elements for consideration to observe the thermal behavior of solar heaters or for research work. But besides this, very authors have paid attention to develop a solar economic system for air heating. In the present article the efforts has been made to estimate the thermal efficiency and payback period (PBP) of solar heater that carry protrusions on its absorber tray. This arrangement was made to increase the heat transfer rate and to improve the efficiency of a simply fabricated SAH. Artificial roughness creates turbulence near the wall and breaks laminar sub-layer. But artificial roughness results in high frictional losses which increases power requirement for fluid flow. The turbulence is created in the region near to heat transferring surface. By this way the efficiency got an enhancement of the solar heater.

For a brief of previous work; Saxena et al [1] has been carried out a literature survey in which the efficiency enhancement techniques of solar air heaters were discussed. The use of extended geometries on the surfaces (absorber/collectors) of SAHs was presented along with the use of some novel thermal heat storage materials. Both methodologies/techniques are used to increase the efficiency of solar energy systems. Alam et al., [2] has been shown the significance of turbulators inside the ducts of SAHs and in heat exchangers on the performance of the systems. Various roughness geometries have been considered to observe the heat transfer and friction characteristics inside SAHs. Results showed that perforation in baffles/ribs/blocks and the combination of delta winglet and rib tends to a better thermo-hydraulic efficiency. Yadav and Thapak [3] have been presented a comprehensive review of SAHs on the basis of experimental research work and computational fluid dynamics [CFD]. Total twenty one type of roughness geometries were considered along with discussion on correlations in between heat transfer function and friction factor inside a SAH. Results showed that in comparisons of large size geometry, the small extended geometries are much influenced the performance of SAHs.

Ozyogurtcu et al [4] has been carried out a techno-economic evaluation of a ventilation system of a hybrid solar unit. The simulation of the system was carried out by TRNSYS 16 in climatic conditions of Turkey. Results shown that the present system reduced the energy consumption around 86% in comparison of conventional ventilation system with an electrical heater. The PBP of the system was estimated to be 5.8 years. Besides this, the efficiency of a SAH can also be increased by some low grade sensible heating materials or by some high grade phase change materials. Saxena et. al., has been used the desert sand [5] and granular carbon [6] to increase the efficiency of a SAH by using them inside the system. After successful experimentation the author used the optimum ration of both the materials [7] and enhances the overall performance of a SAH. In comparison of conventional and costly set-ups of SAH's all the three models [5-7] were found better in thermal performance.

2. Materials and Methodology

There are different methods to evaluate the thermal performance of a SAH according to available designs. The steady-state procedure is commonly used because of involving simultaneous and accurate measurements of mass flow rate ($\dot{m}$), the inlet (T_i) and outlet temperatures (T_o) of the fluid flow and the ambient conditions [5-7]. In the present study, after a change of flow rate, the system was allowed to attain a steady state before the conduction of experiments. Following parameters were obtained to evaluate the thermal performance of the present model.

Mass flow rate $\dot{m} = \rho . A . V$ (1)

[Where: ρ- density of the fluid in kg/m^3, V- flow speed in m/s, A- flow area in m^2]

Equivalent hydraulic diameter

$$d_e = 2LH / L + H \quad (2)$$

[Where: L- length of cross-sectional area of the duct in m, H- height of cross-sectional area of the duct in m]

Reynolds number $\mathrm{Re} = \dfrac{V\rho .2LH}{\mu (L+H)}$ (3)

[Where: μ - dynamic viscosity in kg/(s.m)]

Friction factor $f = \dfrac{0.0791}{(\mathrm{Re})^{0.25}}$ (4)

Pressure drop $\Delta P = 2f(\rho . V^2)\, L/d_e$ (5)

Overall heat transfer coefficient

$$h = \frac{Q_u}{A_p (T_p - T_f)} \quad (6)$$

[Where Q_u (heat supplied to air) $= \dot{m} C_p (T_{op} - T_{ip})$]

Overall heat loss coefficient

$$U_t = \left[\frac{N}{\frac{C_t}{T_P}\left(\frac{T_P - T_a}{N + f_t}\right)^{0.33}} + \frac{1}{h_w} \right] + \left[\frac{\sigma (T_P^2 - T_a^2)(T_P - T_a)}{\frac{1}{\{\epsilon_P + 0.05 \times N(1-\epsilon_P)\}} + \frac{2N + f_t - 1}{\epsilon_g} - 1} \right] \quad (7)$$

[Where; $h_w = 5.7 + 3.8 v_w$ = 8.42 W/m^{2}k, N = 1, $C_t = 520.[1 - 0.0000513 \cdot \beta^2]$ = 519.98 W/m^{2}k, $f_t = (1 + 0.089 \cdot h_w + 0.1166 \cdot h_w \varepsilon_p)(1 + 0.0786 N)$ = 8.97, The bottom heat loss coefficient, $U_b = k_i / t_i$ = 1.75, Applying the value of top loss coefficient and bottom loss coefficient, the overall loss coefficient is determined; $U_L = U_t + (k_i / t)$ = 13.21 W/m^{2}k, $\varepsilon_p = 0.85$, $\varepsilon_g = 0.81$, σ = 5.67 x 10^{-8} W/m^{2}k^4]

Thermal efficiency $\eta \equiv \dfrac{Q_u}{I . A_c} = \dfrac{\dot{m} . C_P (T_o - T_i)}{I . A_c}$ (8)

[Where- A_C - collector surface area (m^2), I - radiation intensity on the absorber (W/m^2), $\dot{m}$ - mass flow rate, T_i - fluid inlet temperature to the collector (°C), T_a - ambient temperature (°C), T_o - outlet temperature (°C), η - efficiency of the collector or system (%), C_P - specific heat of air (kJ/kg-K)]

Figure 1 (a) Experimental set-up of solar air heater

(b) protrusions on absorber tray

Besides this, the purpose of the economic analysis is to evaluate the profitability of a solar energy project and to compare it with alternative investments. A solar energy system can be considered an investment that produces revenue in the form of fuel savings. The alternatives might include an oil-fired boiler, a heat recovery unit, a cogeneration system, or non-energy investments such as stocks, bonds, and real estate. The economic analysis provides the criterion, not only for deciding whether to build a solar energy system, but also for optimizing its design [8].

The simplest way to deal with inflation is based on constant currency and real rates of return (the difference between market rates and the inflation rate) which can be estimated by [9];

$$\frac{1+r_{market}}{1+i} = 1 + r_{real} \tag{9}$$

An amount '*P*' (present worth) is invested at an interest rate '*r*' with annual compounding of interest. After the first year the value increased to $P\ (1 + r)$, after the second year to $P\ (1 + r)^2$ etc. Therefore the future worth '*F*' after '*N*' years is

$$F = P(1+r)^N \tag{10}$$

$$P / F = (1+r)^{-N} \tag{11}$$

[Where the ratio P/F is the present worth factor, and its inverse is the compound amount factor]

If the fuel escalates at a rate 'r_e' then the levelizing of fuel saving, i.e., the levelized fuel price $\bar{P}_e$ can be estimated;

$$\bar{P}_e = \frac{(A/P, r, N)}{(A/P, r_e^{'}, N)} P_e \tag{12}$$

Apart this, the economic analysis of solar energy systems is carried out to determine the least cost of meeting the energy needs, considering both solar and non-solar alternatives. Several criteria can be used to evaluate solar energy systems [10]. The most important factors for the economic analysis of solar energy systems such as solar heaters are as follows;

The capital recovery factor

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1} \tag{13}$$

(While the first annual cost of the system can be estimated by (*CRF*. *P*)

The sinking fund factor can be estimated by;

$$SFF = \frac{r}{(1+r)^n - 1} \tag{14}$$

And the annual salvage value therefore becomes [(*SFF*).*S*]

The annual cost of the system can be estimated by summing the first annual cost and annual maintenance cost and then subtracting the annual salvage value. Where the initial investment in solar energy system is '*P*', with an annual interest rate '*r* %' and '*n*' is the number of useful years up to which the given system will perform.

The net present principal of the investment can be estimated;

$$NPP = \left[\frac{1}{(1+i)} + \frac{1}{(1+i)^2} + \ldots\ldots\ldots\ldots + \frac{1}{(1+i)^t}\right] Z - M \tag{15}$$

The annual cost = interest and principal payments on funds borrowed to install a solar system + fuel or conventional expense + maintenance and insurance + energy costs for running conventional system - income tax savings (16)

While, income tax savings for a non-income producing system, for a solar home heating system, can be estimated by;

Income tax savings = (effective tax rate) x (interest.payment) (17)

If the savings are negative, then they are losses instead of savings. In generalized form the solar savings = cost of conventional energy - costs of solar energy

The annuity factor = $\dfrac{q^L(q-1)}{(q^L-1)}$ (18)

(Where $q=(1+i/100)$, 'i' is the interest rate and L is the lifetime of the SAH)

If 'Q_u' is the net useful energy per unit collector area, collected for the particular days 'd' in a year, from a collector of area 'A', then the price of the energy can be calculated by;

$$P=\frac{C_{ann}}{Q_{ue}.A.d} \qquad (19)$$

(Money which has a present worth of P, its value Z at a future time t, the present money M)

Later on, Slouck has been developed a mathematical model (Lagrangean function) to determine the discounted future benefits and costs of the solar investment. An important economic variable in this estimation was the discount or interest rate. The PBP suggests that it could be used as a guide in the financial evaluation of a solar system. The purpose of the analysis was to clarify what the discount rate should measure by focusing on the decision problem from the homeowner's viewpoint [11]. Dang and Bansal have presented a review of various economic strategies to evaluate solar energy systems. A techno-economic criterion for solar collectors was also presented. The analysis was illustrated with examples of SAHS, solar dryer and solar water heater [12].

Tasdemiroglu and F. Arinic have presented the optimization procedure to maximize the total accumulated saving throughout the economic lifetime of the system. The annual solar heating fraction (SHF) of the system was assessed by using the f-chart method. It was concluded that economic parameters are much more influential on the system economics than the technical parameters. The most significant are the PBP and the internal rate of return. The total cost of the system was calculated with the help of the initial investment and yearly fuel cost necessary to satisfy the heating load, and expressed by [13];

$$C_C=I_C+\sum_{i=1}^{L}\frac{P(i)Q_L}{(1+v)^{(i-1)}} \qquad (20)$$

While the PBP was estimated by;

$$i_o=\frac{In\left\{1+\dfrac{(I_C-I_S)(v-c)}{(1+v)Q_L[P_o-(1-F)P_o^{'}]}\right\}}{In[(1+c)/(1+v)]} \qquad (21)$$

3. Results and Discussion

All the experiments were conducted at the M.I.T, Moradabad-244001. The variation in temperature was measured by using a 6 wire K-type thermocouple meter (accuracy ± 1°C). The solar insolation (W/m^2) was directly measured by a standard solarimeter (CEL-201) {accuracy 1 W/m^2}. The velocity of the air was monitored by an anemometer (accuracy 1m/s). The experiments were repeated for a fixed mass air flow rate (0.12 kg/s on forced convection).

To evaluate the thermal performance of a solar air heater with protrusions on surface, all the experiments were conducted in the month of April 2017 (10.04.2017) from 9:00AM to 18:00 PM. The system was placed towards southward. The wind speed at the inlet duct was measured 2 m/s and kept constant for all experiments. In this testing, the system was found to be taken less time to get hot. At starting (9:00 Hrs) of experiments the T_a was observed 29^{o}C with 595 W/m^2 of solar radiation and ended with 29.5^{o}C with 525 W/m^2 at 18:00 hrs. The T_p was noticed maximum 91.1^{o}C at 13:55 Hrs at noon. The maximum efficiency was found 46.11% while the minimum efficiency was observed 33.45% at 9:00 Hrs (fig 2). The average output exhaust air velocity was 0.95 m/s and the average output temperature was around 44^{o}C.

The value obtained for h_w is 9.1 W/m^{2}K, for C_t is 485.25, for f_t is 4.15, for U_b is 1.71, for U_t is 11.12, for U_L is 12.83 W/m^{2}K, N = 1, σ = 5.67 x 10^{-8} W/m^{2}k^4 and the emissivity of the absorbing plate and glass cover are $\varepsilon_p=0.91$, and $\varepsilon_g=0.81$ respectively. Pressure drop was calculated 0.165 (at velocity of air = 0.95 m/s and f = 0.006) for forced convection respectively for full length 2.82 m, d_e = 0.242, ρ = 1.1 kg/m^3.

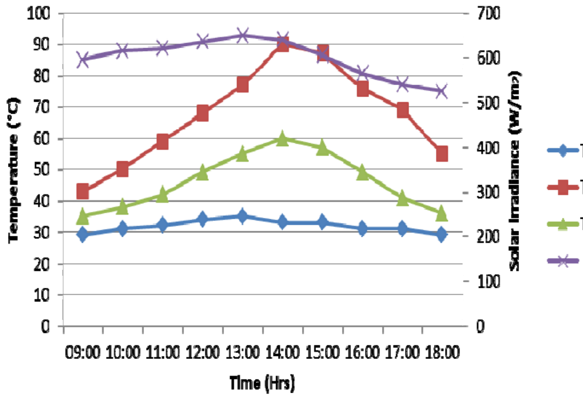

Figure 2 Temperature variations in solar air heater under forced convection

The total fabrication cost of the solar heater was approximately ₹ 5081. The payback period was estimated around 4.41 years by considering the LPG as fuel used for space heating and the cost of LPG is ₹ 28.25. For this, the discount rate was taken 10%, maintenance cost was taken 5% cost of SAH and life span was 6 year. In comparison of other conventional solar heaters, the present system is quite better in terms of thermal performance, however the overall loss coefficient is high but the thermal efficiency is also high.

4. Conclusion

A solar air heater has been tested for thermal performance evaluation under the climatic conditions of Moradabad, India. The system was carried a blackened absorber tray with symmetrical protrusions on the surface. The system was tested for 9 hours in a summer day under forced convection for a fixed flow rate. The thermal efficiency of the system was found to be 46.11 with an overall heat loss coefficient of W/m^{2}K. The payback period of the system was estimated around 4.41 years. The system was found better in terms of thermal performance in comparison of other conventional solar heaters (without protrusion surfaces).

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