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Performance Evaluation of Hybrid Solar Water Heating System Using Wire Screen Packed Solar Air Heater

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ABSTRACT
The requirement of hot water for domestic purposes is one of the needs that can be fulfilled by water heating system utilizing solar energy. In the present work a solar air heater packed with wire matrix is used to increase temperature of water and to store solar energy in a water heating system which is attached to it through an air to water heat exchanger. The study was carried out on a hybrid solar water heating system using wire screen packed solar air heater as well as conventional solar air heater. Data pertaining to heat transfer characteristics were collected for air flow rate ranging from 0.005 to 0.04 kg/s-m^2 for six sets of matrices with varying geometrical parameters of solar air heater and water storage tank.

It has been found that performance depends on the geometries parameters of the wire screen matrix used as packing in the solar air heater.It was also founded that with increase in storage tank capacity, there is decrease in storage tank temperature and as mass flow rate increases there is increases in storage tank temperature.

The dimensions of solar air heater are found to affect the performance of the hybrid water heating system. The effectiveness of heat exchanger is also a crucial factor as it is the part which gives heat to water. **On comparing the**performance of hybrid system using conventional as well as matrix packed solar air heater. It is found that the thermal efficiency of system using packed bed air heater is found to be significantly better than that when we use conventional solar air heater.

Keywords: Packed bed solar air heater, Hybrid Water heating system, Heat exchanger, Storage tank, Conventional Solar air heater

I. Introduction

Solar water heaters are the systems in which we use solar energy for heating water. Some typical and commercial designs of solar water heaters are:

1. Natural circulation solar water heater.
2. Forced circulation solar water heater.

The major drawback in conventional solar water heating system is that these systems are not susceptible to mineral build up from hard water. Also, if installed in cold climate, there may be a damage to water heater due to corrosion and freezing of water in the collector: channels.This problem can be solved by following three methods

1 The use of solar collector with antifreeze liquids as the heat transfer fluid and liquid to-waterheat exchanger. In these systems antifreeze liquid like glycol carries heat from the collector and gives away its heat to water in liquid to water heat exchanger. Antifreeze liquid with corrosion inhibitors increases the life of the system.

2. The use of solenoid valve or mechanical valve in the collectors to drain the water from them when their temperature reaches freezing point. Mechanical valves are operated using temperature sensor. When temperature decreases to freezing point the valves are opened to drain water from it.
3. The use of solar air heaters which must use a heat exchanger for hot water heating.

Both [1,2]suggested Hybrid solar collector comprising an air to water heat exchanger because of its simplicity in plumbing and elimination of frosting and corrosion problem. Additional advantages of the hybrid air-to-water heating systems are their use for multipurpose applications such that the outlet air from the heat exchanger can be used for space heating, crop drying, etc. However, the efficiency of such system can further be enhanced using packed bed solar air heaters which have significantly better thermal efficiency compared to conventional air heaters [3]. There are different types of packed bed air heaters based on the packing element used. Out of them construction of wire mesh packed bed solar air heater is simple and convenient.

II. MODEL DESCRIPTION

A schematic flow diagram of the system under consideration is shown in Fig. 2. The present system has three seperate units: air heater, air-to-water heat exchanger; and hot water storage tank. these three units are connected to each other insulate pipesand there is no loss of heat through them.

For compairison two types of air heater has been used

1. Solar air heater packed with wire matrices For calculations different sets of matrices are those chosen as used by Varshney [4]. For performance studies of solar collector, the geometrical parameters of the matrix used are given in Table I and the wire screen geometry is shown in Fig. 3.
2. Conventonal Solar air heater. Figure 1 shows schematic diagram of the typical conventional solar air heater. It consists of two sheets of glass covers and back plate. This type of collector has a continuous passage in the form of duct beneath the absorber plate. Air is passed through the duct from
3. one end to the other. Air comes in contact with the entire absorber plate and picks up heat.

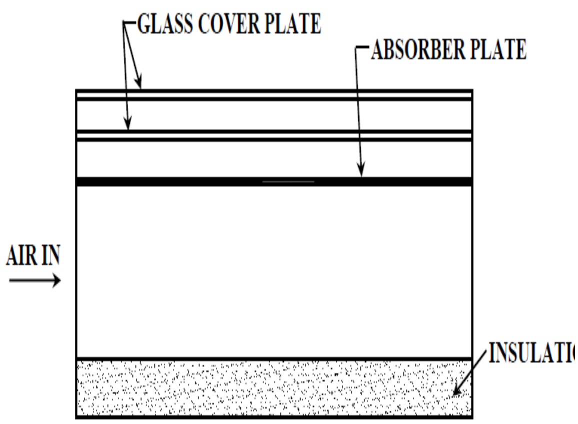

Fig. 1 Schematic of conventional solar air heater

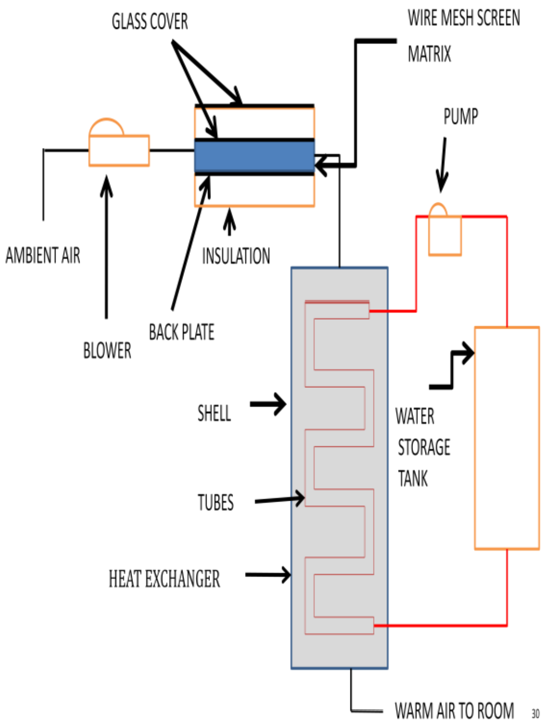

Fig.2 Schematic view of the Hybrid Solar Water Heating System

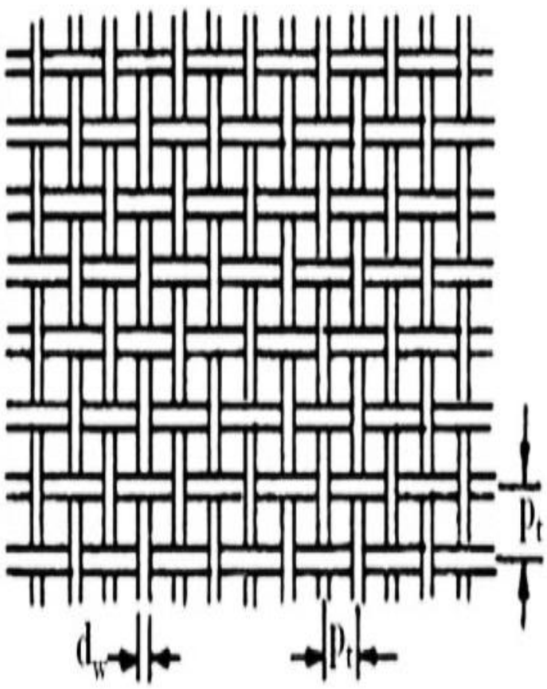

Fig.3 Wire Screen geometry used as a packing element

Table I Geometrical parameters of wire screen matrix[4]

Parameters	M1	M2	M3	M4	M5	M6
Porosity	0.958	0.939	0.902	0.887	0.905	0.937
Wire diameter, mm	0.036	0.450	0.590	0.795	0.795	0.795
Pitch, mm	2.72	2.08	2.23	3.19	3.19	3.19
No of layers	14	10	10	9	7	5
Bed depth, m	0.025	0.025	0.025	0.025	0.025	0.025
Extinction coefficient m^{-1}	170.4	210.8	224.3	183.2	142.6	102.4

III. MATHEMATICAL MODELLING

Solar air heater with wire mesh

Expression of effective thermal conductivity, k_e developed by Yagi and Kunii[5] withflowing fluid has been used which is given below:

$$k_e = k_e^o + (k_e)_t \qquad (1)$$

$(k_e)_t$is the thermal conductivity caused by lateral mixing of the fluid.

$$(k_e)_t = (\alpha'\beta')D_e C_P G_0 \qquad (2)$$

(□ □ □ □) for steel wire mesh screens has been used as 0.12 which is the average of total range 0.1 to 0.14 in which the value lies for different packing reported byYagi and Kunii[5].

D_e is equivalent diameter of the sphere which is expresses as:

$$D_e = 6/a_v \qquad (3)$$

k_e^0has been calculated using the following equations [5]

$$k_e^0 = \frac{1+P^{1.3}}{\frac{1}{k_p+h_{rv}D_e P^{1.3}/(1-P^{1.3})}+\frac{1}{\left(\frac{k_g}{\varphi}\right)+h_{rs}D_e}} + \frac{16(n')^2\sigma T_b^3}{3\beta} + \frac{4h_{rv}P^{1.3}D_e k_P}{k_P+\frac{h_{rv}D_e P^{1.3}}{1-P^{1.3}}+\left(\frac{k_g}{\varphi}\right)+h_{rs}D_e} \qquad (4)$$

$\varphi$is the ratio of effective thickness of fluid film adjacent to the contact surface of the two solid particles to mean diameter of solid. Numerical value of $\varphi$is taken as 0.12[6].

h_{rv} andh_{rs} are the heat transfer coefficients for thermal radiation from solid surface to solid and from void to void and can be expressed as [4]:

$$h_{rs} = 0.1952\,\{\varepsilon/(2-\varepsilon)\}\{T_b/100\}^3 \qquad (5)$$

$$h_{rv} = \left[0.1952/\left\{1+\frac{P}{2(1-P)}\frac{1-\varepsilon}{\varepsilon}\right\}\right]\left(\frac{T_b}{100}\right)^3 \qquad (6)$$

The following assumptions have been made to simplify the analysis.

1. The temperature distribution within individual packing element and glass coveris uniform.
2. Conductive heat transfer in the flow direction is negligible.
3. Natural convection is not generated in the flow duct.
4. Physical properties of the packed bed material are independent of the temperature.
5. For the evaluation of the top losses, the value of top loss coefficient has been determined by equation 7.

Klein [7] recommended an empirical correlation for the top loss coefficient for a range of absorber plate temperature up to 200 °C. This correlation predicts top loss coefficient, U_t within ± 0.3 W/m^2K and is given by:

$$U_t = \left[\frac{N}{(C/\overline{T_P})\left[\overline{(T_P}-T_a)/(N+f_t)\right]^e}+\frac{1}{h_W}\right]^{-1} + \frac{\sigma\left(\overline{T_P}^2+T_a^2\right)\left(\overline{(T_P}+T_a\right)}{(\varepsilon_P+0.00591\,N\,h_W)^{-1}+[(2\,N+f_t-1+0.133\varepsilon_P)/\,\varepsilon_P]-N} \qquad (7)$$

Where,

f_t = $(1+0.089\,h_w - 0.1166\,hw\,\varepsilon_P)(1+0.07866\,N)$

e = $0.43(1-100/t_p)$

c = $520(1-0.000051\,s^2)$ for $0^0 \leq s \leq 70^0$

For $70 \leq s \leq 90$, use $s = 70^0$

Heat balance equations have been modified for quasi steady state conditions in the analysis of the collector bed. While writing the heat balance equations, conduction losses through the side and back walls have been neglected. Further, the environmental temperature and wind velocity have been assumed uniform and constant.

The heat balance equations can be obtained as follows for the packed bed collector operating under actual outdoor conditions.

(Net heat flux entering the element due to conduction) + (Net heat flux due to radiation) = (Rate of heat gained by the air by means ofconvection from matrix to air) (8)

(Rate of rise in the sensible heat of air) = (Rate of energy carried away by the air) (9)

The mathematical expression of eq. 8 can be rewritten as:

$$\frac{\partial}{\partial y}\left(Ke\frac{\partial T_b}{\partial y}-Qr\right) = h_c a_v (Tp-Tg) \qquad (10)$$

The bed temperature $T_b$is assumed to be average of matrix temperature Tpand air temperature Tg
Therefore:

$$\frac{\partial}{\partial y}\left[k_e \frac{\partial t_b}{\partial y} - Q_r\right] = 2h_c a_v (t_b - t_g) \quad (11)$$

Where,

$$Q_r = I_y - R_y = R_1 e^{-\tau} - R_2 e^{-(\tau_0 - \tau)} \quad (12)$$

The mathematical expression of eq. 9 can be rewritten as:

$$Go\ Cp \frac{\partial Tg}{\partial x} = 2Hc\ Av\ (Tb - Tg) \quad (13)$$

The solution is obtained using n on-dimensionlisationand discretization of equations using boundary conditions. Average outlet temperature, t_o, is determined by averaging the air temperature at the last nodal points. For example let suppose last nodal point is N1.
Average outlet temperature is given by:

$$t_0 = \frac{t \sum_{j=1}^{M} v_{i,j}{}_i}{M} \ at\ i = N1 \quad (14)$$

The rate of useful thermal energy gain of the collector can be expressed as follows:

$$Q_u = \dot{m} C_P (t_0 - t_i) \quad (15)$$

Conventional Solar air heater
The correlation used for heat transfer coefficients in the conventional flat plate collector is given by Kays and Crawford**.**[8]

$$Nu = 0.0158\ Re^{0.8} \quad (16)$$

Where, the characteristics length is the hydraulic diameter which is twice the plate spacing.
The top loss coefficient is given in eq. 7. But in this air heater there are other losses also occurred as back losses. The sum of other losses back and side is assumed to be of 1 W/m^2.

Heat exchanger
Maximum heat transfer from the air to water is

$$Q_{max} = \dot{m} C_{pa} (t_{a2} - t_{w1}) \quad (17)$$

Useful heat transfer from the air to water is

$$Q_u = \varepsilon_h * Q_{max} \quad (18)$$

Water storage tank

$$T_S^+ = T_S + \frac{\Delta t}{(m C_p)_s} Q_u \quad (19)$$

Thus the temperature at the end of an hour is calculated from that at the beginning, assuming that temperature do not change during the hour.

Determination of Thermal efficiency
Thermal efficiency is the ratio of useful heat gain in system to the total solar radiation incident on solar air heater.

Thermal efficiency $(\eta_{thermal} = (\frac{\text{Total Useful heat gain (Qu)}}{\text{Total Solar Insolation}})$ (20)

Computer Program
A computer program has been developed in MATLAB 2009, to compute the results. The flow chart of the program has been given in Appendix which evaluates the coefficients of all the equations and then these coefficients are placed in the form of a matrix. The solution of the matrix generates the non dimensional bed and air temperatures. These non-dimensional temperature are then converted to temperature in degree Celsius. Average outlet temperature is determined by eq. 14.then maximum heat transfer has been calculated and then useful heat gain being evaluated. Once useful heat gain is evaluated, storage tank temperature can be calculated from eq.18 after every hour of operation of system.Values of system and operating parameters used for evaluation of storage tank temperature are given in Table II.

IV. RESULTS AND DISSCUSSIONS

The total sunshine duration is assumed to be of 8 hours with an average flux of 900W/m ^{2} and ambient temperature as 35.5 ^{0}C. The analysis is done by varying various parameters like mass flow rate, geometry of matrices, storage tank capacity, etc. The temperature of water in storage tank is initially at 26 ^{0}C. The results obtained from mathematical model are discussed below.

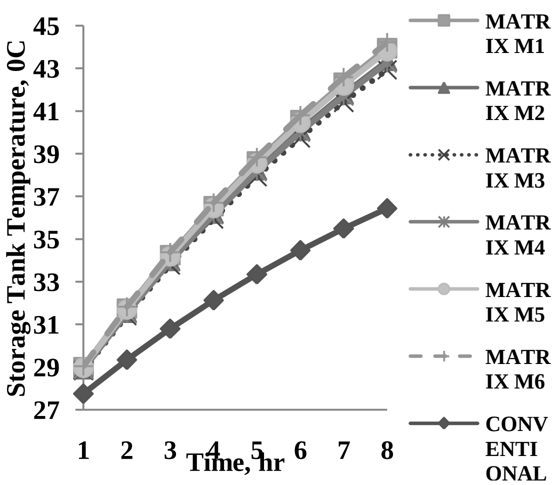

Fig. 4 the variation of storage tank temperature with time for different wire screen matrices

Figure1shows the variation of storage tank temperature with time for different wire screen matrices and smooth flat plate collector. The storage tank temperature is calculated for mass flow rate of 0.0098 kg/s-m^2 having 50 kg capacity of storage tank. The storage tank temperature monotonously keeps on increasing with time. This behaviour can be attributed to the fact that there is no loss of heat from the tank and the energy is continuously added.

It is also observed that the storage tank temperature obtained with matrix M6 is maximum and minimum for matrix M3. This behaviour is obvious as the heat transfer coefficient obtained with matrix M6 is maximum, resulting in maximum tank temperature. Matrix.

This can be explained on the basis of geometry of the matrix. For different matrix the geometrical parameters are different and the heat transfer coefficient for each matrix can be calculated using the correlation reported by Varshney and Saini[3] which comes out to be maximum in case of matrix M6 and hence it can be concluded heat transfer coefficients is a function of parameters of matrix.

Fig.5 and figure 6 shows variation of storage tank temperature with time for different tank capacity with matrix 6 and matrix 3. Variation of storage tank temperature with time for different tank capacity with matrix M6 yielding the best performance, The capacity of storage tank is varied from 30 kg to 70 kg. As storage tank capacity increases, storage tank temperature decreases. It is obvious as capacity of the tank increases, more the heat is required for raising the water temperature, but the insolation flux is same for all capacities of tanks. So with the increase in tank capacity the maximum temperature reached by the storage tank should be decreased.

Similar plots are drawn taking matrix M3 and using conventional solar air heater.

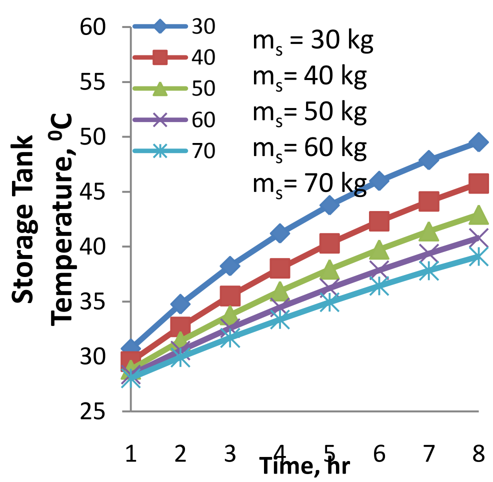

Fig. 5 Variation of storage tank temperature with time for different tank capacity with matrix 6.

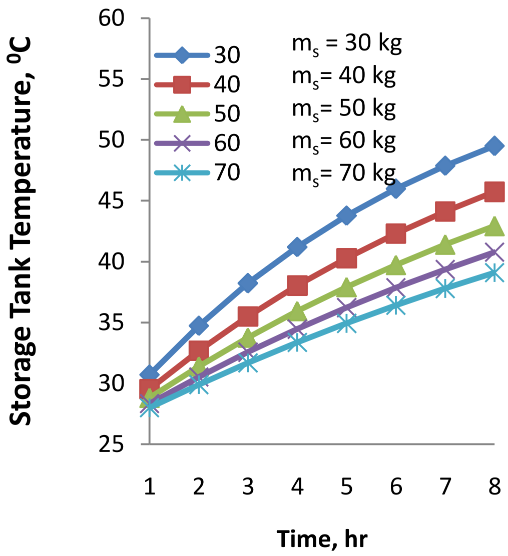

Fig. 6 Variation of storage tank temperature with time for different tank capacity with matrix 3.

Variation of storage tank temperature with solar air collector length for wire screen matrices M6 and M3 and for conventional flat plate collector has been depicted in Fig.7. Value of mass flow rate of air of 0.0098 kg/sm^2 and storage tank capacity of 50 kg have been taken. As the length of solar air collector increases there is an increase in storage tank temperature. Initially up to collector length of about 0.5 m the storage tank temperature after 8^{th} hour is approximately same as in case of conventional solar air heater. After collector length of 0.5 m the use of wire matrix yield better results as the storage tank temperature is higher as compared to the conventional solar air heater. There is a significant increase in storage tank temperature after the length is more than 1 m as compared to conventional solar air heater.

In the initial length, the amount of energy is less which is utilized in increasing the temperature of the matrix and the temperature of the matrix and the effective transfer of heat to the air is less and even same to the flat plate collector. The amount of energy transfer keeps increasing with length. Also the energy is absorbed in depth in matrix which results in decreased amount of loss there by resulting in still better temperature rise.

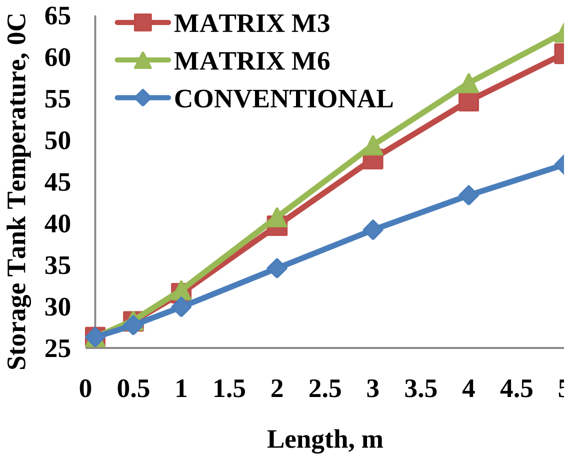

Fig. 7 Variation of storage tank temperature with time for different tank capacity with matrix 6.

V. CONCLUSIONS

On the basis of analytical results, the following conclusions were drawn:

1. The storage tank temperature of hybrid solar water heating system using solar air heater packed with wire matrix is relatively higher as compared to hybrid solar water heating system using conventional solar air heater.

2. The storage tank temperature depends on the geometric properties of the matrix. The maximum value of storage tank temperature is obtained with solar air heater packed with matrix M6 and minimum value is for matrix M3.

3. It is found that with the increase in storage tank capacity there is decrease in storage tank temperature. Therefore, one has to check the tank capacity as per the temperature requirement.

4. The length of air collector have been found to be a strong parameter affecting the tank temperature accordingly these parameters should be chosen as per requirement of storage tank temperature.

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