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ORIGINAL ARTICLE

Performance parameters evaluations of solar water heating systems using low cost plastic porous and non-porous absorber collectors along with air/water heat exchanger in a closed loop cycle and hot water storage tank

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Abstract

Many times, solar water heating systems lead to problems like leaking and corrosion. Air heaters generally are free from corrosion and leakage is also not a several problems. Moreover, the use of plastics has brought down the prices of air heating collectors drastically. Using this concept a novel, A novel on solar water heating systems using air/water heat exchanger connected with low-cost plastic films solar collector in a closed loop cycles and thermal model has been proposed. Explicit expressions for useful energy and thermal efficiency have been obtained for air-based temperature and water-based temperatures and dynamic model was proposed for open and closed loop cycles. The utility of the thermal model was established by conducting experiments on various systems for several days and results of extensive theoretically and experimental studies are presented. Closed agreement between theoretical and experimental results validates the proposed methodology.

1. Introduction

Energy is a critical input in the national development process. In fact, it is the basic requirement for human life, agriculture, industry, and many other economic activities of the present civilization. In the present day, the depleting fossil fuels in the various countries, the terms of energy crises underline the need of paying serious attention to the effective /efficient utilization of existing conventional and non-conventional energy sources in terms of energy conservation through effective management for maximum agricultural production. Thermal performance of a flat-type honeycomb porous bed solar air heaters in which air flows perpendicularly from the transparent cover to a porous absorber plate with a mass flow rate of m > 40 kg/m^{2}h have been evaluated and found the best operating efficiency obtained when running the collector thermal performance is superior than channel type solar air heaters operating under similar conditions [1-3]. The problem inhibiting the popular use of solar water heating systems is the cost of the delivered useful energy which has to be estimated with proper techno-economics. The numerical calculations are made for Indian market conditions and Delhi (India) climate for open loop water heating systems and closed loop water heating systems, with a heat exchanger in the collector loop. The basic problem which deserves to be considered for all types of solar water heating systems is the optimization of the collector with respect to the cost of useful delivered energy for various storage capacities. It was observed from computation that the cost of solar energy comes out to be more than for electrical energy which has been highly subsidized in the alternative systems. The cost of useful delivered energy comes out around the cost of

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electrical energy without a subsidy and 10% less with a subsidy. The optimized collector area for 70°C desired temperature for 200 litres. of daily hot water demand comes out to be 2.5 m^2 for 180 litres. of tank capacity and 2 m^2 with a heat exchanger in the collector loop.

The cost of the useful delivered energy will be more if an auxiliary heating system is provided inside the storage tank instead of at load. For a forced flow system, the cost of the delivered useful energy comes out 15% higher [4]. The accurate TRNSYS simulation program can be in simulating different configuration of forced circulation solar water heating systems, and to inspect the most prominent parameters that affect the discrepancy between simulation and experiment which showed the discrepancy in the position of the temperature sensors controlling the circulation of the pump [5]. Economic analysis developed by Mishra [6, 7] showed that the use of conventional materials for solar water heating is still prohibitive for their large-scale use. Both suggested the use of solar water heating system using air heater connected with air/water heat exchanger. The use of air heater takes care of corrosion and leakage problems which are severe for solar water heating collectors. Also, the cost of an air heaters fabricated from conventional materials is however still too prohibitive. Bansal suggested the use of plastic materials and developed an efficient air heating plastic porous and non-porous absorber collector. Taking this concept, an efficient novel solar water heating systems have been developed and tested. The performance equations for such systems have been designed and accurate theory was developed and comparison with the experimental measurements made. This concept coming out to be more attractive and some more calculations for solar air heaters were performed and results have been presented in this paper. Expressions for the performance parameters F', U_L and F_R of various collector configurations which consists of an air-heating collector connected to a compact air/water heat exchanger, these performance parameters derivations have not been documented.The derivation of performance parameters is accomplished for an air/water heating system by considering duct losses in the solar water heating systems have been carried out.The utility of these performance parameters in finding the rating parameters of an air/water heating system and mutual comparisons of various of these parameters for other systems also investigated [6]. A dimensionless analysis of matrix air heaters has been developed to study the effect of different boundary conditions on its performance [7]. The authors compared theoretical results compared with measurements of an experiment performed with matrix solar air heater and found the fourth set of boundary conditions, the theoretical results agree fairly well with experimental data, and compared with other suitable boundary conditions. For this particular set of boundary conditions, the thermal performance of the system have been compared for different mass flow rates of air and as a function of other physical parameters and found that 10 to 15% higher thermal performances than using non porous solar air heating collectors depending on the particular designs [6].A simple solar air heater from cheap plastic wrapping film with air bubbles, for use in drying operations on a farm (grain, fruit, fish, etc.) developed by investigator and Theoretical model was used was a single-sheet cylindrical collector and, after it had gained some heat, another layer of the plastic wrapping film with air bubbles was added in a later stage to decrease convection heat losses to the surroundings. Each cylindrical collector was 5m long and 0.36 m in diameter, with a black interior band covering the lower part of the collector (30% of the surface area). The inlet direction of the collector was always towards the wind in order to achieve maximum air flow inside the collector and found the considerable gain in the temperature of the airflow a temperature difference of around 10°C. A theoretical and experimental study including the combined convective and radiative heat transfer analysis of a flexible cylindrical type solar air - heater for circular and two elliptic shapes with 0.55 and 0.65 m major axis are presented. The solar collector is manufactured from films acting as a black absorber with a back insulation and double transparent covers sealed together along its edges. The collector is to be blown with a flow of pressurized air. A computer program is written for calculating the outlet temperature and collector thermal efficiency. Moreover, the Nusselt number between the absorber and the heated air is determined experimentally in relation with the Reynolds number. Comparisons between the experimental data and the theoretical methods for the collector efficiency demonstrate a good agreement [6]. In addition of this, the present experimental results of Nusselt number are correlated and compared [8].

2. Transient thermal analysis of solar water heating systems using low cost porous and non-porous absorber plastic air heating collectors

For closed loop system, we considered a storage tank is connected to air/water heat exchanger. The storage tank is carried an auxiliary heater. The energy balance equation in the storage tank is given by following governing equation.

$$M_wC_{pw}\,[dT_w(t)/dt]+U_TA_T(Tw(t)-Ta(t))+(\beta(m_L\times C_{pw})\times(T_w(t)-T_i\,(t))=[(m_w\times C_{pw}\times(Tw_2(t)-T_w(t))+f_1Q_{Aux})] \quad (1)$$

Where, $[f_1Q_{Aux}]$ = amount of auxiliary energy used and $[f_1]$ can be taken as 0 or 1 depending on whether Tw(t) at any instant is ≥ or ≤ the desired temperature T_d $[U_TA_T(Tw(t)-Ta(t))]$ is the energy lost from hot water storage tank. $[\beta(m_L\times C_{pw})\times(T_w(t)-T_i\,(t))]$ is the hot water (energy) withdrawal from hot water storage tank. $M_wC_{pw}\,[dT_w(t)/dt]$ is the rate of energy storage in the hot water storage tank in terms of internal energy. Rearranging Eq. [1] we get following differential equation.

$$[dT_w(t)/dt]+[\{(U_TA_T)+(\beta(m_L\times C_{pw})+(m_w\times C_{pw})/(M_wC_{pw})]T_w(t) = [(U_TA_T\,T_a(t))+(\beta(m_L\times C_{pw}T_i\,(t))+(m_w\times C_{pw}T_{w2}(t))/(M_wC_{pw})] \quad (2)$$

From the air/water heat exchanger equation, the $[T_{w2}(t)]$ in terms of $[T_w(t)]$ can be expressed as

$$[T_{w2}(t)] = [(T_{a1}(t) - T_{a1}(t)\exp(-(h_f A_E/(m_w \times C_{pw}))) + T_{w2}(t)\times \exp(-(h_f A_E/(m_w \times C_{pw})))] \quad (3)$$

where $A_E = (p_1 \times L_1)$ is the area of air/water heat exchanger (m^2) Substituting the value of $[T_{w2}(t)]$ from equation [3] in eq. [2] we get

$$[dT_w(t)/dt]+[\{(U_T A_T)+(\beta(m_L \times C_{pw})+(m_w \times C_{pw}) /(M_w C_{pw})]T_w(t)= [\{f_1 Q_{Aux})+(U_T A_T\, T_a(t))+(\beta(m_L \times C_{pw} T_i(t))\}/ (M_w C_{pw})]]+[\{(m_w \times C_{pw})/(M_w C_{pw})\}\times\{(T_{a1}(t)\times(1-(\exp(-(h_f A_E/(m_w \times C_{pw})))) + T_w(t)\times(\exp(-(h_f A_E/(m_w \times C_{pw}))))] \quad (4)$$

Let

$$T_{a1}= [(\beta_2/\beta_4) - (\beta_3/\beta_4)\, T_{a2}(t)] \quad (5)$$

Where $\beta_1 = \exp(-(h_f A_c/(m_a \times C_{pa}))$

$\beta_2 = [(\tau\alpha)\mathrm{eff}\times A_c I_t(t)+ U_{Lc} A_c T_a]$, $\beta_3 = m_a \times C_{pa} + U_{Lc} A_c\{\beta_1/(1-\beta_1)\}$

$\beta_4 = [m_a \times C_{pa} + U_{Lc} A_c\{1/(1-\beta_1)\}]$ and Let $U_1= \exp(-(h_a A_E/(m_w \times C_{pw})))$ and $U_2 = \{(m_w \times C_{pw})\times(1-U_1)/(h_f A_E)\}$

Where $[h_f]$ is the total heat transfer coefficient in the air/water heat exchanger. Considering energy balance in the air/water heat exchanger

$$[m_w \times C_{pw}\{(T_{w2}(t) - T_w(t))\} = (h_f \times A_h)\Delta T_{LMTD}] \quad (6)$$

$$\Delta T_{LMTD} = [\{(T_{a1}(t) - T_{a2}(t)) - (T_{w2}(t) - T_w(t))\}/\{\log_e((T_{a1}(t) - T_{w2}(t))/(T_{a2}(t) - T_w(t))\}] \quad (7)$$

Substituting for ΔT_{LMTD} in the equation[7] in eq.[7] we gets

$$M_w \times C_{pw}\{(T_{w2}(t) - T_w(t))\}= [(h_f \times A_h)\{(T_{a1}(t) - T_{a2}(t)) - (T_{w2}(t) - T_w(t))\}/\{\log_e((T_{a1}(t) - T_{w2}(t))/(T_{a2}(t) - T_w(t))] \quad (8)$$

in terms of U_1 and U_2, the eq.[8] can be written as

$$\{(T_{a1}(t) - T_{a2}(t)) - \{(1-U_1)T_{a1}(t))+(U_1 \times T_{w1}(t) - T_{w1}(t)) / [(m_w \times C_{pw}/(h_f A_E))\times((1-U_1)T_{a1}(t))+(U_1 \times T_{w1}(t) - T_{w1}(t))]= \log_e[\{(T_{a1}(t) - U_1 T_w(t))-(1-U_1)T_{a1}(t))\}/((T_{a2}(t) - T_w(t))] \quad (9)$$

Rearrange eq. 9

$$(T_{a2}(t)= [T_w(t)+ U_1(T_{a1}(t))-T_w(t))\times(\exp\{(T_{a1}(t))- U_1 T_{a2}(t)(1-U_1)T_w(t))/(U_2(T_{a1}(t))-T_w(t))\}] \quad (10)$$

Eq. [10] is transcendental equation and it is solved by using an iterative technique. When the auxiliary heater is provided outside the tank f_1 becomes zero and auxiliary is calculated by using following expression.

$$Q_{Aux} = m_L \times C_{pw}(T_d - T_w(t)) \quad (11)$$

Where $[T_d]$ is desired constant temperature of hot water at the load point. Naturally for $[T_w(t)] \geq T_d$, $Q_{Aux} = 0$

2.1 Performance parameters for solar water heating systems using low cost porous and non-porous absorber plastic air heating collectors in a closed loop cycle

The rate of useful energy gain in the solar water heating system using air/water heat exchanger connected with plastic air heating collector can be written as

$$Q_u = m_a C_{pa}(T_{a1} - T_{a2}) \quad (12)$$

$$Q_u = m_w C_{pw}(T_{w2} - T_{w1}) \quad (13)$$

$$Q_u = h_a A_h * \Delta T_{LMTD} \quad (14)$$

Where

$$\Delta T_{LMTD} = \{[\tfrac{1}{2}]C[\Delta T_1 + \Delta T_2]\} \quad (15)$$

Where C=0.95

$$\Delta T_1 = [T_{a1} - T_{w2}] \quad (16)$$

$$\Delta T_2 = [Ta_2 - Tw_1] \quad (17)$$

Substituting Eq.[16] and eq.[17] in eq.[15],one gets

$$\Delta T_{LMTD} = \{[\tfrac{1}{2}]C[(T_{a1}+T_{a2}) - (T_{w2} - T_{w1})] \quad (18)$$

The energy balance equation for whole system can be expressed as

$$Q_u = [\{A_c(\tau\alpha)I_t\} - U_E A_E\{((Tw_2+Tw_1)/2)-T_a\}-[U_{Lc} A_C\{(Ta_2+Ta_1)/2)-T_a\}] \quad (19)$$

Where

$U_E\ A_E\ \{((Tw_2+Tw_1)/2)-T_a\}$ is the energy lost from the air/water heat exchanger and $[U_{Lc}\ A_C\ \{(Ta_2+Ta_1)/2)-T_a\}]$ is the energy lost from porous and non-porous absorber air heating collector.

$[A_c\ (\tau\alpha)I_{t]}$ is the energy absorbed by the porous and non-porous absorber air heating collector. The outlet water in the heat exchanger can be calculated as $[Tw_2]$ is calculated by following expression

$[Tw_2]= [Tw_1] + Q_u/(m_w C_{pw})$ and

$$(Ta_2+Ta_1)/2) = (Tw_2+Tw_1)/2)+[Qu/(h_a C A_h)] \quad (20)$$

and for plastic air heating solar collector, the outlet air temperature can be written as

$$T_{a1}= T_{a2} + Q_u/(m_a C_{pa}) \quad (21)$$

Substituting the value of $(Ta_2+Ta_1)/2)$ from equation [20] in Eq. [19] one gets

$$Q_u = [\{A_c(\tau\alpha)I_t\} - U_E A_E \{((Tw_2+Tw_1)/2) - T_a\} - [U_{Lc} A_C \{(Tw_2+Tw_1)/2) - T_a\}] + Q_u [U_{Lc} A_C/(h_a C A_h)] \quad (22)$$

$$Q_u [1+\{U_{Lc} A_C/(h_a C A_h)\}] = [\{A_c(\tau\alpha)I_t\} - [\{U_E A_E + U_{Lc} A_C\} * \{((Tw_2+Tw_1)/2) - T_a\}] \quad (23)$$

$$Q_u = [1+\{U_{Lc} A_C/(h_a C A_h)\}]^{-1} [A_c [\{(\tau\alpha)I_t\} - [U_E A_E + U_{Lc} A_C\} \{(Tw_2+Tw_1)/2) - T_a\}] \quad (24)$$

Which is the similar equation of HWB type in terms of water based can be written as

$$Q_u = F' A_\epsilon[(\{(\tau\alpha)I_t\} - U_L ((Tw_2+Tw_1)/2) - T_a\}] \quad (25)$$

Where

$$F' = [1+\{U_{Lc} A_C/(h_a C A_h)\}]^{-1} \quad (26)$$

and

$$U_L = [(U_E A_E + U_{Lc} A_C)/A_{c]} \quad (27)$$

Substituting the value of outlet temperature of water in the air/water heat exchanger, the energy balance equation of whole system in terms of inlet water temperature in air/water heat exchanger can be expressed as

$$Q_u = [1+\{U_{Lc} A_C/(h_a C A_h)\}]^{-1} [A_c [\{(\tau\alpha)I_t\} - [U_E A_E + U_{Lc} A_C\}\{(Tw_1 - T_a\}] - [U_E A_E + U_{Lc} A_C\}\{Q_u/(2 m_w C_{pw}) \quad (28)$$

Rearranging eq [28] one gets following expression in terms of inlet water temperature

$$Q_u = [1+\{U_{Lc} A_C/(h_a C A_h)\} + \{(U_E A_E + U_{Lc} A_C)/(2 m_w C_{pw})]^{-1} [\{A_c(\tau\alpha)I_t\} - [U_E A_E + U_{Lc} A_C\}\{(Tw_1 - T_a\}] \quad (29)$$

Which is the similar equation of HWB type in terms of inlet water based temperature can be written as

$$Q_u = F_R A_\epsilon[(\{(\tau\alpha)I_t\} - U_L ((Tw_2+Tw_1)/2) - T_a\}] \quad (30)$$

Where

$$F_R = [1+\{U_{Lc} A_C/(h_a C A_h)\} + \{(U_E A_E + U_{Lc} A_C)/(2 m_w C_{pw})]^{-1} \quad (31)$$

The performance parameters can be obtained by substituting$(Tw_2+Tw_1)/2)$ in terms of air temperature based expressed as

$$Q_u = [\{A_c(\tau\alpha)I_t\} - U_E A_E \{((Ta_2+Ta_1)/2) - T_a\} - [U_{Lc} A_C \{(Ta_2+Ta_1)/2) - T_a\}] + Q_u [U_E A_E/(h_a C A_h)] \quad (32)$$

Rearranging eq. [32] one gets following expression in terms of average air-based temperatures and inlet air temperature.

$$Q_u [1+[U_E A_E/(h_a C A_h)] = [\{A_c(\tau\alpha)I_t\} - U_E A_E \{((Ta_2+Ta_1)/2) - T_a\} - [U_{Lc} A_C \{(Ta_2+Ta_1)/2) - T_a\}] \quad (33)$$

$$Q_u [1+\{U_E A_E/(h_a C A_h)\} + \{(U_E A_E + U_{Lc} A_C)/(2 m_a C_{pa}\}] = [\{A_c(\tau\alpha)I_t\} - \{(U_E A_E + U_{Lc} A_C)\}\{((Ta_2+Ta_1)/2) - T_a\} \quad (34)$$

Eqs[22] and eq. [34] can be written as in terms of HWB equation form in terms of average air temperature based

$$Q_u = [1+[U_E A_E/(h_a C A_h)]^{-1}] [\{A_c(\tau\alpha)I_t\} - (U_E A_E + U_{Lc} A_C)\{((Ta_2+Ta_1)/2) - T_a\}] \quad (35)$$

$$Q_u = F' A_\epsilon[(\{(\tau\alpha)I_t\} - U_L ((Tw_2+Tw_1)/2) - T_a\}] \quad (36)$$

Where

$$F' = [1+\{U_E A_E/(h_a C A_h)\}]^{-1} \quad (37)$$

and

$$U_L = [(U_E A_E + U_{Lc} A_C)/A_{c]} \quad (38)$$

Similarly

$$Q_u = [1+\{U_E A_E/(h_a C A_h)\} + \{(U_E A_E + U_{Lc} A_C)/(2 m_a C_{pa}\}]^{-1} [\{A_c(\tau\alpha)I_t\} - \{(U_E A_E + U_{Lc} A_C)\}\{((Ta_2 - T_a\}] \quad (39)$$

Which is the similar equation of HWB type in terms of inlet air based temperature (T_{a2}) can be written as

$$Q_u = F_R A_\epsilon[(\{(\tau\alpha)I_t\} - U_L ((Ta_2 - T_a\}] \quad (40)$$

$$F_R = [1+\{U_{Lc} A_C/(h_a C[20] A_h)\} + \{(U_E A_E + U_{Lc} A_C)/(2 m_w C_{pw})] \quad (41)$$

3. Results and Discussion

It was found that the linear approximation for the Hottel-Bliss equation leads to erroneous estimations for the collector's parameters when the absorber is porous; for the same type of collector with a denser textile as absorber, however, such an approximation yields, as usual, correct numerical values for the characteristic parameters of the collector. The specifications of solar water heating systems made of plastic air heating collectors are given in table-1 respectively. Transient thermal model was developed to evaluate thermal performance of solar water heating systems using low-cost porous absorber plastic collector coupled with air/water heat exchanger in the closed loop cycle and theoretical results were compared with experimental measured data in the closed loop cycle in which 360 litres hot water storage tank was connected with air/water heat exchanger in the closed loop cycle is shown in table-2(a, b) respectively. It was found that developed thermal models results matched with experimental measurements with slight variations due to nonlinear random variations of ambient temperature and solar radiation.

Table 1: Dimension of solar energy components used in solar air/water heating systems

S. N0	Dimensions/parameters	Porous Absorber	Non-Porous Absorber	PVC Absorber
1	Length of Solar Collector	10.0 m	9.15 m	9.10 m
2	Width of Solar Collector	1.0 m	0.92 m	1.10 m
3	Absorber Area	10 m^2	9.02 m^2	10.01 m^2
4	Material of cover	PVC	Fluoropolymer	PVC
5	Thickness of top cover	0.7 mm	0.6mm	0.6mm
6	Transmittance of the top PVC cover in the solar spectrum range	0.90	0.94	0.83
7	Thickness of inside cover	0.60 mm	0.30 mm	0.30 mm
8	Material of the cover	PVC Black	PVC Black	PVC Black
9	Transmittance of the inside cover in the solar spectrum range	0.90	0.94	0.83
10	Material of Porous Absorber	Black porous textile cloth	Black PVC	Black PVC
11	Thickness of Absorber	1.8 mm	0.6mm	0.6mm
12	Material of tubes of Air/water Heat exchanger	Copper	Copper	Copper
13	Diameter of tubes of heat exchanger	12.5 mm	12.5 mm	12.5 mm
14	Materials of Fins of the heat exchanger	Copper	Copper	Copper
15	Wattage of motor of blower	480 W	480 W	480 W

Table 2(a) outlines the thermal performance of a solar water heating system connected to a 360-litre storage tank operating in a closed-loop cycle without any hot water withdrawal throughout the day. The data spans from 7:00 A.M. to 6:00 P.M., showcasing variations in solar insolation (measured in W/m²) alongside corresponding hot water storage tank temperatures obtained both through thermal modeling and experimental observation. In the early hours of the morning, solar insolation begins at 50 W/m², gradually rising as the sun ascends, reaching a peak of around 750 W/m² between 12:00 P.M. and 1:00 P.M. Correspondingly, the temperature of the stored water increases progressively from 22.5°C to a peak of 46.5°C by 5:00 P.M. The temperature values predicted by the thermal model are in close agreement with experimental measurements throughout the day, demonstrating the accuracy and reliability of the thermal modeling approach. This steady increase in temperature, coupled with the absence of hot water withdrawal, highlights the system's effective thermal energy capture and storage capability. The results clearly indicate that the solar water heating system can maintain and increase water temperature efficiently under favorable insolation conditions when there is no demand.

Table 2(b), on the other hand, presents the 24-hour hot water consumption profile for a 400-litre system, capturing typical usage patterns throughout the day and night. The data reveals a bimodal demand trend, with two prominent peaks. The first major consumption period is between 6:00 A.M. and 10:00 A.M., during which the highest demand occurs, notably peaking at 72 litres between 8:00 A.M. and 9:00 A.M. This reflects common household or residential use during morning activities. Following this, minimal and sporadic withdrawals continue throughout the day in relatively small amounts ranging from 6 to 24 litres, maintaining a low consumption rate. A complete absence of water withdrawal is recorded between 6:00 P.M. and 1:00 A.M., indicating inactivity during the evening and early night. However, a second significant demand spike emerges between 2:00 A.M. and 3:00 A.M., with a withdrawal of 190 litres, followed by moderate use until 6:00 A.M., which could be attributed to shift-based industrial or institutional activities. The understanding gained from comparing the performance profile in Table 2(a) with the demand pattern in Table 2(b) is essential for improving the design and operation of solar water heating systems.

Table 2(a): Performance of solar water heating system connected with 360 litres of hot water storage tank in a closed loop cycle without hot water withdrawal

Time (1/2) hrs	Insolation (W/m^2)	Hot water storage tank temp (°C) (Model)	Hot water storage tank temp (°C) Exp.
7.0 A.M	50	22.5	22.5
7.30	150	23.7	23.6
8.0	250	25.0	24.7
8.30	313	26.2	26.0
9.0	375	27.5	27.3
9.30	425	29.0	28.7
10.0	472	30.0	29.5
10.30	560	34.1	33.8
11.0	650	37.5	37.1
11.30	700	40.2	40.0
12.0	750	42.5	42.1
12.30 P.M	748	43.1	42.9
13.0	745	43.6	43.3
13.30	710	44.1	43.9
14.0	675	44.5	44.3
14.30	625	44.9	44.7
15.0	575	45.2	45.0
15. 30	505	45.7	45.5
16. 0	325	46.0	45.8
16. 30	195	46.2	46.1
17. 0	150	46.5	46.0
17. 30	95.0	46.5	45.7
18. 0	25	46.0	45.5

Table 2(b): Hot water Demand Profile of 400 litres

Time (hr)	Hot water withdrawal (Litres)
6AM to 7.0	10
7 – 8	48
8.-9	72
9-10	60
10-11	06
11-12	08
12-13 P.M	08
13-14	08
14-15	08
15-16	08
16-17	20
17-18	24
18-19 PM.	0.0
19-20	0.0
20-21	0.0
21-22	0.0
22-23	0.0
23-24	0.0
1. A.M.	0.0
2-3	190
3-4	40
4-5	40
5-6 AM	40

The developed transient thermal model was employed to assess the thermal performance of a solar water heating system incorporating a low-cost porous absorber plastic collector and an air/water heat exchanger, connected to a 360-litre hot water storage tank in a closed-loop configuration. This model aimed to predict the system's behavior under realistic operating conditions and was validated against experimental data collected under scenarios involving 400 litres of daily hot water withdrawal. The withdrawal pattern used for evaluation is presented in Table 2(b), and the system performance over the second and third days—both with and without water withdrawal—is illustrated in Tables 2(c) and 2(d), respectively.

The comparison revealed a close match between the model predictions and the experimental results under both conditions, demonstrating the reliability and accuracy of the developed thermal model. Minor deviations were observed, which can be attributed to the non-linear and random nature of ambient temperature variations and fluctuating solar radiation throughout the day.

Table 2(c) presents the system's performance on the second day. The initial temperature of the hot water storage tank at 7:00 A.M. was 40.0°C for both scenarios (with and without withdrawal). As solar insolation increased during the day, the system without hot water usage exhibited a continuous and steady rise in water temperature, reaching a peak of 60.5°C by 4:00 P.M. and slightly declining thereafter due to reduced solar input. On the other hand, the system experiencing 400 litres of daily hot water withdrawal showed a significantly lower thermal performance, with the tank temperature only reaching a maximum of 42.0°C around 3:00 P.M. This marked difference underscores the impact of water withdrawal on thermal energy retention and system efficiency.

Similarly, Table 2(d) presents data from the third day of operation. Due to the cooling effect from nighttime and the heat lost due to the previous day's hot water usage, the system began with a lower temperature of 28.5°C at 7:00 A.M. for both cases. The system with no withdrawal once again demonstrated consistent heating throughout the day, achieving a maximum temperature of 50.3°C by late afternoon. In contrast, the system subjected to water withdrawal displayed a more moderate temperature increase, peaking at just 40.0°C before beginning to decline. These observations consistently confirm that continuous hot water usage reduces the system's ability to store and build up thermal energy, while the absence of withdrawal allows for greater energy accumulation and retention.

Overall, the results highlight the necessity of designing solar water heating systems with sufficient thermal storage capacity and proper insulation to counteract daily consumption. Additionally, incorporating auxiliary heating mechanisms may be essential in meeting user demand during periods of low solar availability or high usage. The close alignment between the model and experimental data also confirms the model's robustness in simulating transient thermal behavior under variable operating conditions, making it a valuable tool for system optimization and performance forecasting.

Table 2(c): Performance of solar water heating system connected with 360 litres of hot water storage tank in a closed loop cycle without hot water withdrawal of second day

Time (1/2) hrs	Insolation (W/m^2)	Hot water tank temp of second Day without hot water with-drawal (°C)	Hot water storage tank temp of second Dawith 400 daily hot water with-drawal (°C)
7.0	50	40.0**	40.0***
7.30	150	40.8	39.1
8.0	252	42.0	38.0
8.30	313	43.8	37.0
9.0	377	46.0	36.0
9.30	425	48.5	36.3
10.0	470	51.2	36.5
10.30	560	52.6	37.1
11.0	638	54.1	38.0
11.30	700	55.6	38.4
12.0	739	57.0	39.0
12.30	748	57.8	39.5
13.0	735	58.5	40.0
13.30	712	59.1	40.5
14.0	670	59.6	41.0
14.30	625	59.8	41.5
15.0	560	60.0	42.0
15. 30	507	60.3	41.2
16. 0	330	60.5	40.0
16. 30	196	60.2	39.1
17. 0	125	60.0	38.0
17. 30	95.0	59.8	37.1
18. 0	25.0	46.0	36.2***

Table 3(a) presents the performance parameters of a solar water heating system that utilizes a porous absorber plastic collector integrated with an air/water heat exchanger operating in a closed-loop cycle. The two main parameters shown are F'(τα)e, the effective product of the collector efficiency factor and transmittance-absorptance, and F'ULe, the effective product of the collector efficiency factor and overall heat loss coefficient. These parameters provide insight into the thermal behavior and efficiency of the collector system. The values of F'(τα)e range from 0.425 to 0.465, indicating moderate solar energy absorption efficiency. A higher value, such as 0.465 (entry 10), signifies better utilization of solar radiation due to improved transmittance and absorption characteristics of the collector. On the other hand, lower values, such as 0.425 (entries 14 and 15), suggest slightly reduced optical performance, possibly influenced by material properties or aging effects. In contrast, the F'ULe values show a broader variation, ranging from 3.056 to 4.044 W/m²·°C. A lower F'ULe value like 3.056 (entry 12) is desirable as it indicates minimal heat loss to the surroundings, implying effective insulation and thermal retention. Conversely, a higher value such as 4.044 (entry 13) reflects increased thermal losses, which could be attributed to environmental factors or reduced insulation performance.

Table 2(d): Performance of solar water heating system connected with 360 litres of hot water storage tank in a closed loop cycle without hot water withdrawal of third day

Time (1/2) hrs	Insolation (W/m^2)	Hot water tank temp (°C) without withdrawal	Hot water storage tank temp (°C) of third Day with 400 litres of daily water withdrawal
7.0	50	28.5	28.5***
7.30	150	30.0	30.0
8.0	248	32.0	32.0
8.30	315	33.1	31.5
9.0	373	34.5	31.0
9.30	424	34.6	30.5
10.0	438	37.0	30.0
10.30	560	38.4	30.7
11.0	650	39.5	31.5
11.30	700	40.8	32.0
12.0	740	42.0	32.5
12.30	748	43.5	33.8
13.0	735	45.0	35.0
13.30	707	46.2	37.6
14.0	675	47.5	38.0
14.30	621	48.7	39.1
15.0	575	49.9	40.0
15. 30	502	50.1	39.6
16. 0	323	50.2	39.1
16. 30	190	50.3	38.6
17. 0	150	50.3	38.3
17. 30	95.0	50.2	37.8
18. 0	25	50.0	37.2

The performance parameters of such novel water heating systems using porous absorber plastic collectors with air/water heat exchanger presented in table-3(a) respectively. The solar air heating collectors simply consists of black plastic film covered with transparent PVC in which textured polyester black cloth absorber. These air heating collectors has an thermal efficiency up to 45% to 72% but has the advantage that they need not be protected or washed very often for removal of dust. Although plastic collectors have the disadvantage of shorter life time in comparison with conventional system, however, makes the economics of plastic made air heating collectors much more acceptable than the conventional materials.

Table 3(a): Performance parameters of solar water heating systems using porous absorber plastic collector connected with air/water heat exchanger in the closed loop cycle.

S.No	$F'(\tau\alpha)_e$	$F'U_{Le}$
10	0.465	3.72
11	0.4535	3.4356
12	0.450	3.056
13	0.450	4.044
14	0.425	3.733
15	0.425	3.6956

The average thermal performance of water heating systems using non porous absorber plastic collectors with air/water heat exchanger for different days have been presented in table-3(a) respectively. The solar air heating collectors simply consists of black plastic film covered with transparent PVC. These air heating collectors has an thermal efficiency up to 35% to 45% but has the advantage that they need not be protected or washed very often for removal of dust. Although plastic collectors have the disadvantage of shorter life time in comparison with conventional system, however, makes the economics of plastic made air heating collectors much more acceptable than the conventional materials. The average performance parameters of solar water heating systems using non porous collector connected in air/water heat exchanger in a closed loop cycle is shown in table-3(c) and average thermal efficiency was found to be 29.3%.

Table 3(b): average daily Performance of closed loop solar water heating systems using non porous absorber plastic collector connected with air/water heat exchanger in the closed loop cycle

Date	Insolation (kW)	Useful energy (kW)	Thermal Efficiency
9th May 1985	7.6	2.56	0.3370
10th May 1985	17.25	4.5	0.2610
11th May 1985	18.80	4.73	0.2520
12th May 1985	19.35	5.4	0.2790
13th May 1985	16.31	5.46	0.2350

Table 3(c): Performance parameters of solar water heating systems using non porous absorber plastic collector connected with air/water heat exchanger in the closed loop cycle

S.No	$F'(\tau\alpha)_e$	$F'U_{Le}$
1	0.347	3.541
2	0.3750	3.75
3	0.2950	3.6875
4	0.305	3.588
5	0.2950	3.6875

4. Conclusion

Transient thermal model was developed to evaluate thermal performance of solar water heating systems using low cost porous & non porous absorber plastic collector coupled with air/water heat exchanger in the closed loop cycle and 360 litres of hot water storage tank and theoretical results were compared with experimental measured data in the open loop cycle. It was found that developed thermal models results matched with experimental measurements with slight variations due to nonlinear random variations of ambient temperature and solar radiation.

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