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RESEARCH ARTICLE

Thermal Modelling of some solar air and water heating systems using low-cost porous and non-porous air heating collectors

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Abstract

This paper explores the concept of using heated air to generate hot water through both open and closed-loop cycles. The plastic film collectors, previously studied by Bansal et al. (1983), were constructed in a closed-loop cycle, incorporating a heat exchanger in the middle of the system. Performance equations for this system were derived in the form of the HWB equation. Additionally, dynamic analysis for both open and closed-loop systems was proposed. The results from the proposed model were validated by comparing them with experimentally measured values. Furthermore, a comparison between the studied system and conventional water heating systems was presented, highlighting the efficiency and performance differences. The study provides valuable insights into the potential benefits of using heated air and innovative collector designs for water heating, offering a comprehensive analysis of system dynamics and validation through experimental data.

1. Introduction

Large scale use of solar energy for various application is still prohibitive. Irrespective to the application, heating water by solar energy still remains to be one of the widely acceptable uses of solar energy. Another concept of heating water is to first heat air and then transfer the energy of heated air to water by using a compact air/water heat exchanger. Though this concept introduces one more step of heat exchange, and detailed studies at Colorado state university pointed out that air heating systems collect solar energy at nearly the same efficiency as the water heating systems [1]

1.1 Porous and Non-porous air heating solar collectors

The air heating systems have distinctly two advantages over water heating systems.

- Corrosion problems are nearly absent in air heaters.
- Leaking of fluid is not as serious as it is in the case of water heaters.

The above two advantages in air heaters allow the use of low-cost materials. Bansal et. al) described novel air heating collectors made from plastic films. Two types of collectors have been described i.e. (i) porous absorber collectors and (ii) non-porous absorber collectors. In the farmer, the absorption of solar radiation takes place over a textile cloth absorber, which acts as a matrix porous absorber air heating collector. The heat transfer takes place over a volume resulting in very high efficiency up to 70% The later variety of solar air heating collectors simply consists of black plastic film covered with transparent PVC. These air heating collectors has a thermal efficiency up 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

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much more acceptable than the conventional materials [2,3].

2. Thermal Analysis of open loop solar water heating system using low-cost plastic collector connected to air/water heat exchanger

Many times, solar water heating collectors lead to a problem like leaking and corrosion and air heaters generally are free from corrosion and leaking system. Moreover, the use of plastic collectors has brought down the prices of air heating collectors drastically. Using this concept, a novel solar water heating system was designed and studied using open and closed loop air heating collector with an air/water heat exchanger and dynamic model is developed. The air heating collectors under study is a closed loop type, which was connected to air/water heat exchanger. The solar collectors belong to the both categories such as (i) porous and non-porous type absorber of non-porous blackened PVC films of 0.6mm thickness and it is attached to a transparent sheet of polyvinyl chloride (PVC) and were fabricated from flexible plastic sheet absorber and another systems also using textured polyester as black absorber of 1.8mm thickness in the porous type of collectors with results of an extensive theoretical and experimental studies have been presented by using following energy balance equations in the open loop cycle [4].

$$[(\tau\alpha)\text{eff}\times A_c I_t(t) - (U_{Lc}\, A_c(T_p - T_a)] = m_a\times C_{pa}\times(T_{a1}(t) - T_{a2}(t) \quad (1)$$

Where T_{a1} is the air outlet temperature of air heating collector and T_{a2} is the air inlet temperature of air heating collector (which is air inlet to air/water heat exchanger). The the air inlet temperature of air heating collector (T_{a1}) can be obtained from following expression.

$$[dT_f/ (T_p - T_f)] = [h_f\, p\, m_a\times C_{pa})]\, dx \quad (2)$$

The solution p dx / (of equation yields to following equation

$$\text{Log}_e [\, T_p - T_a] = [h_f\, m_a\times C_{pa})] + \text{Constant} \quad (3)$$

At x=0, $T_f = T_{a2}$ and Hence equation

$$T_{a1} = [T_p + (T_{a2} - T_p)\times\exp(-(h_f\, A_c /(m_a\times C_{pa}))] \quad (4)$$

Where, $A_c = (p\times L)$ is the area of air heating solar plastic collector(m^2) and $\beta_1 = \exp(-(h_f\, A_c /(m_a\times C_{pa}))$ then

$$T_{a1} = [T_p - \beta_1 (T_{a2} - T_p)] \quad (5)$$

Rearranging equation (5) one gets

$$T_p = [\, \{1/(1-\beta_1)\}T_{a1} - \{\beta_1/(1-\beta_1)\}\, T_{a2}] \quad (6)$$

Substituting the value of [Tp] from equation [6] in eq.[1] we gets

$$[(\tau\alpha)\text{eff}*A_c I_t(t) - (U_{Lc}\, A_c([\, \{1/(1-\beta_1)\}T_{a1} - \{\beta_1/(1-\beta_1)\}\, T_{a2}] - T_a)] = [m_a*C_{pa}*(T_{a1} - T_{a2})] \quad (7)$$

Rearranging equation (7) one gets

$$T_{a1} = [(\beta_2/\beta_4) - (\beta_3/\beta_4)\, T_{a2}] \quad (8)$$

Where,

$\beta_2 = [(\tau\alpha)\text{eff}*A_c I_t(t) + U_{Lc}\, A_c\, T_a]$,
$\beta_3 = m_a*C_{pa} + U_{Lc}\, A_c\{\beta_1/(1-\beta_1)\}$
$\beta_4 = [m_a*C_{pa} + U_{Lc}\, A_c\{1/(1-\beta_1)\}]$

The Eq. [8] gives outlet temperature of air heating plastic collector. The energy balance equation in the air/water heat exchanger can be written as

$$m_w\times C_{pw}\,[dT_w/ dy]\, dy = [h_a\, p_1(T_{a1} - T_w)dy \quad (9)$$

At y=0, $T_w = T_{a1}$ and $y=L_1$, $T_w = T_{w1}$

$$T_{w2}(t) = [(T_{w1} - T_{a1})\exp(-(h_a\, A_E /(m_w*C_{pw})) + T_{a1})\exp(-(h_a\, A_E /(m_w*C_{pw}))] \quad (10)$$

Where
$A_E = (p_1\times L_1)$ is the area of air/water heat exchanger ($m^{2)}$ and $[h_a]$ is the total heat transfer coefficient in the air/water heat exchanger Substituting the value of $[T_{a1}(t)]$ from equation[8] in eq.[10] we gets

$$T_{w2}(t) = [(\beta_2 + \beta_3)/\beta_4\,]T_{a2}(t)*[1-(\exp(-(h_a\, A_E /(m_w*C_{pw}))))] + [T_{w1}(t)*(\exp(-(h_a\, A_E /(m_w*C_{pw}))))] \quad (11)$$

Let $\alpha_1 = \exp(-(h_a\, A_E /(m_w*C_{pw})))$, $\alpha_2 = (\beta_2 / \beta_4)$ and $\alpha_3 = (\beta_3 / \beta_4)$

Substituting the value of $\alpha_1, \alpha_2, \alpha_3$, in eq.[11] we gets

$$T_{w2}(t) = [\{(\alpha_2 + \alpha_3\, T_{a2}(t))\times(1-\alpha_1)\} + \alpha_1 T_{w1}(t)] \quad (12)$$

Considering energy balance in the air/water heat exchanger

$$[m_w*C_{pw}\,\{(T_{w2}(t) - T_{w1}(t))\} = (h_a*A_E)\Delta\, T_{LMTD}] \quad (13)$$

Where Again substituting the value of $T_{a1}(t)$ and $\Delta\, T_{LMTD}$, from eq. [14] we gets

$$\Delta\, T_{LMTD} = [\{(T_{a1}(t) - T_{a2}(t)) - (T_{w2}(t) - T_{w1}(t))\} /\{\log_e((T_{a1}(t) - T_{w2}(t))/(T_{a2}(t) - T_{w1}(t))\}] \quad (14)$$

$$(T_{a1}(t) - T_{a2}(t)) - \{(\alpha_2 + \alpha_3\, T_{a2}(t))*(1-\alpha_1)\} + \{(T_{w1}(t)\,\alpha_1) - T_{w1}(t))\}\ \log_e[\{(T_{a1}(t) - \{(\alpha_2 + \alpha_3\, T_{a2}(t))*(1-\alpha_1)\} + (T_{w1}(t)\,\alpha_1)\}/ (T_{a2}(t) - T_{w1}(t))]\ [(m_w*C_{pw} / (h_a\, C\, A_h)(\alpha_2 + \alpha_3 T_{a2}(t)*(1-\alpha_1)\} + T_{w1}(t)\,(\alpha_1 - 1)]\, \} \quad (15)$$

Let $Z_1 = \{\beta_2/\beta_4\}$, $Z_2 = [\{\beta_3/\beta_4\} - 1]$, $Z_3 = \alpha_2(1-\alpha_1)$, $Z_4 = (\alpha_1 - 1)$, $Z_5 = \alpha_3(1-\alpha_1)$ and $Z_6 = \{m_w*C_{pw} / (h_a\, C\, A_h)\}$

then equation (15) can be written as

$$[\{(Z_1-(Z_4 T_{w1}(t)+Z_3)+\{(z_2+z_5)T_{a2}(t))\,]\,/\,[\{Z_6*(Z_3+Z_4 T_{w1}(t)+Z_5T_{a2}(t)\} = \log_e[\{(Z_1-(Z_3+\alpha_1 T_{w1}(t)+z_5T_{a2}(t)\}/(T_{a2}(t)-T_{w1}(t))] \quad (16)$$

Again rearranging eq. [16] one gets

$$(T_{a2}(t)\exp(Z_2-z_5)-(z_6\,z_5)T_{a2})-(z_5\exp\{-(Z_1-z_4 T_{w1}(t))+z_3-z_6(Z_3+z_4 T_{w1}(t)) = [(Z_1-(Z_3+\alpha_1 T_{w1}(t))\exp(-\{(Z_1-Z_4 T_{w1}(t)+Z_3)-z_6(z_3+z_4 T_{w1}(t))] \quad (17)$$

2.1 Closed cycle (loop) analysis

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.

$$M_wC_{pw}[dT_w(t)/dt]+U_TA_T(Tw(t)-Ta(t))+(\beta(m_L*C_{pw})*(T_w(t)-T_i(t)) = [(m_w*C_{pw}*(Tw_2(t)-T_w(t))+f_1Q_{Aux})] \quad (18)$$

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 .$[\beta(m_L*C_{pw})*(T_w(t)-T_i(t))]$ 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

$$dT_w(t)/dt+[\{(U_TA_T)+(\beta(m_L*C_{pw})+(m_w*C_{pw})/(M_wC_{pw})]T_w(t) = [(U_TA_T\,T_a(t))+(\beta(m_L*C_{pw}T_i(t))+(m_w*C_{pw}T_{w2}(t))/(M_wC_{pw})] \quad (19)$$

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

$$[T_{w2}(t)] = [(T_{a1}(t)-T_{a1}(t)\exp(-(h_f A_E/(m_w*C_{pw}))) + T_{w2}(t)*\exp(-(h_f A_E/(m_w*C_{pw})))] \quad (20)$$

Where $A_E = (p_1*L_1)$ is the area of air/water heat exchanger ($m^{2)}$. Substituting the value of $[T_{w2}(t)]$ from equation [3] in eq.[19] we gets

$$[dT_w(t)/dt]+[\{(U_TA_T)+(\beta(m_L*C_{pw})+(m_w*C_{pw})/(M_wC_{pw})]T_w(t) = [\{f_1Q_{Aux})+(U_TA_T\,T_a(t))+(\beta(m_L*C_{pw}T_i(t))\}/(M_wC_{pw})]]+[\{(m_w*C_{pw})/(M_wC_{pw})\}*\{(T_{a1}(t)*(1-(\exp(-(h_f A_E/(m_w*C_{pw})))) + T_w(t)*(\exp(-(h_f A_E/(m_w*C_{pw}))))] \quad [21]$$

Let $T_{a1} = [(\beta_2/\beta_4)-(\beta_3/\beta_4)\,T_{a2}(t)]$ [22]

Where

$\beta_1 = \exp(-(h_f A_c/(m_a*C_{pa}))$, $\beta_2 = [(\tau\alpha)eff*A_cI_t(t)+U_{Lc}A_c T_a]$

$\beta_3 = m_a*C_{pa}+U_{Lc}A_c\{\beta_1/(1-\beta_1)\}$, $\beta_4 = [m_a*C_{pa}+U_{Lc}A_c\{1/(1-\beta_1)\}]$,

Let $U_1 = \exp(-(h_a A_E/(m_w*C_{pw})))$, $U_2 = \{(m_w*C_{pw})*(1-U_1)/(h_f A_{E)}\}$

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

$$[m_w*C_{pw}\{(T_{w2}(t)-T_w(t))\} = (h_f*A_h)\Delta T_{LMTD}] \quad (23)$$

Where,

$$\Delta T_{LMTD} = [\{(T_{a1}(t)-T_{a2}(t))-(T_{w2}(t)-T_w(t))\}/\{\log_e((T_{a1}(t)-T_{w2}(t))/(T_{a2}(t)-T_w(t))\}] \quad (24)$$

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

$$m_w*C_{pw}\{(T_{w2}(t)-T_w(t))\} = [(h_f*A_h)\{(T_{a1}(t)-T_{a2}(t))-(T_{w2}(t)-T_w(t))\}/\{\log_e((T_{a1}(t)-T_{w2}(t))/(T_{a2}(t)-T_w(t))] \quad (25)$$

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

$$T_{a2}(t) = [T_w(t)+U_1(T_{a1}(t))-T_w(t))*(\exp\{(T_{a1}(t))-U_1 T_{a2}(t)-(1-U_1)T_w(t))/(U_2(T_{a1}(t))-T_w(t))\}] \quad (26)$$

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.

$$Q_{Aux} = m_L*C_{pw}(T_d-T_w(t)) \quad (27)$$

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

3. Results and Discussion

The dimensions and specification of components of three solar water heating systems using plastic air heaters are shown in Table-1(a) to Table-1(d) respectively.

Table 1(a): Dimensions of solar water heating systems using plastic air heating collectors connected with air/water heat exchanger

Type of collector	Porous Plastic Collector	Porous Plastic Collector	Porous Plastic Collector	Porous Plastic Collector
Porous Absorber Area (m^2)	9.12	10.12	19.89	10
Non-Porous Absorber Area (m^2)	10	9.12	9.89	9.02

Table-1(b): Specifications of plastic solar air heating collectors

S.No.	Dimensions/parameters	Porous Absorber	Non-Porous Absorber	PVC Absorber	Porous Absorber
1	Length of Solar Collector	10.0 m	9.15 m	9.10 m	10.0 m
2	Width of Solar Collector	1.0 m	0.92 m	1.10 m	1.0 m
3	Absorber Area	10 m^2	9.02 m^2	10.01 m^2	10 m^2
4	Material of cover	PVC (Transparent)	Fluoro- polymer	PVC	PVC
5	Thickness of top cover	0.7mm	0.6mm	0.6mm	0.6mm
6	Transmittance of the top PVC cover in the solar spectrum range	0.90	0.94	0.83	0.90
7	Thickness of inside cover	0.60 mm	0.30 mm	0.30 mm	0.60 mm
8	Material of the cover	PVC Black	PVC Black	PVC Black	PVC Black
9	Transmittance of the inside cover in the solar spectrum range	0.90	0.94	0.83	0.90
10	Material of Porous Absorber	Black porous textile cloth	Black PVC	Black PVC	Black porous textile cloth
11	Thickness of Absorber	1.8 mm	0.6mm	0.6mm	1.8 mm
12	Material of tubes of Air/water Heat exchanger	Copper	Copper	Copper	Copper
13	Diameter of tubes of heat exchanger	12.5 mm	12.5 mm	12.5 mm	12.5 mm
14	Materials of Fins of the heat exchanger	Copper	Copper	Copper	Copper
15	Wattage of motor of blower	480 W	480 W	480 W	480 W

Table-1(c) : Heat exchanger inputs

S.No.	Specification of Air/Water heat exchanger	Value
1	Maximum power extractable from heat exchanger	2.8kW
2	Air inlet temperature	70°C
3	Air outlet temperature	50°C
4	Air volume flow rate	500 m^3/hr
5	Cold water inlet temperature	10°C
6	Water outlet temperature	55°C
7	Water mass flow rate	0.05 (m^3/hr)
8	Pressure drop of water	0.04 Bar
9	Air pressure drop(of H_2O)	20 mm

Table-1(d) Input Data used in the Air/water heating systems using plastic collectors

S.No	Input Parameters	Value
1	Water heat transfer coefficient (h_f)	120 (W/°C)
2	Water mass flow rate (m_w)	0.0833 (kg/sec)
3	Overall heat loss coefficient (U_L)	22.5 (W/m²°C)
4	Area of Air/water Heat exchanger (A_E)	1.2164 m^2
5	Effective Area of Air/water Heat exchanger	0.264 m^2
6	Overall air heat transfer coefficient(h_a)	22.0 (W/m²°C)

The study investigates the performance of an open and closed-loop solar water heating system using air/water heat exchangers connected to low-cost plastic collectors. The parameters used in the system, as presented in Table-1(c) and Table-1(d), provide crucial insights into the system's operating conditions and performance characteristics. In Table-1(c), several key specifications for the air/water heat exchanger are listed, including a maximum power extractable value of 2.8 kW, which indicates the system's potential for heat transfer. The air flows through the system at a rate of 500 m³/hr, entering at 70°C and exiting at 50°C, transferring heat to the water, which enters at 10°C and exits at 55°C. The water mass flow rate is 0.05 m³/hr, and the pressure drops for water and air are 0.04 Bar and 20 mm of H2O, respectively. These values help determine the overall performance and efficiency of the heat exchanger in transferring heat from the air to the water. In Table-1(d), parameters such as the water heat transfer coefficient (120 W/°C) and the overall heat loss coefficient (22.5 W/m²°C) provide further details on the system's ability to transfer and maintain heat. The effective area of the air/water heat exchanger, which is 0.264 m², and the air heat transfer coefficient (22.0 W/m²°C) also play significant roles in optimizing heat exchange between the two mediums. The system was tested over several days, with data from the open-loop cycle provided in Table-2(a), helping evaluate the system's real-world performance. This data supports the analysis of the system's heat transfer efficiency, pressure losses, and overall functionality, which are crucial for optimizing the design of solar water heating systems.

The performance of open plastic solar collectors with air/water heat exchangers (Ac = 10m²) was evaluated over several days in May 1985, with the results summarized in Tables 2(a) to 2(e). These results are critical in assessing the system's thermal performance, offering insights into how effectively the system transfers solar energy to heat water. Several key parameters were measured during the experiments, including the temperature difference across the air/water heat exchanger, mass flow rate of water, insolation, useful energy (Qu), and thermal efficiency. The temperature difference across the air/water heat exchanger is a key factor in heat transfer. Over the experimental period, this temperature difference varied between 7.7°C and 14.3°C, with the highest values observed on 12th May 1985, indicating periods of optimal heat transfer. The mass flow rate of water was maintained at around 300 L/hr, ensuring consistent water circulation, which is crucial for efficient heat absorption. The solar radiation or insolation also fluctuated throughout the days, with values ranging from 516 W/m² to 885 W/m². These variations in insolation directly impacted the amount of energy absorbed by the system.

Useful energy (Qu), representing the heat transferred to the water, ranged from 1492 W to 2548 W on 9th May 1985. Higher useful energy values were observed during peak sunlight hours, indicating the system's ability to capture and transfer energy effectively. The thermal efficiency, calculated as the ratio of useful energy to solar energy input, varied between 0.132% and 0.418% on 9th May. On subsequent days, thermal efficiency generally ranged from 0.230% to 0.373%, showing that the system maintained stable performance throughout the testing period. These values indicate that the system's thermal efficiency is comparable to conventional solar water heating systems, which is promising for further optimization. In comparing these results with conventional systems, the efficiency is reasonable, and the system's cost-effectiveness, due to the use of low-cost plastic collectors and air/water heat exchangers, suggests that it could offer substantial savings. Although the system's efficiency is not extraordinarily high, it performs on par with conventional systems, and improvements in design, such as optimizing the heat exchanger's surface area and reducing heat losses, could enhance its efficiency. Further testing with porous absorbers, as shown in Tables 2(f) to 2(i), demonstrated experimental results that closely matched theoretical predictions, further validating the model's accuracy. This agreement between theory and experiment supports the potential for refining and scaling the system for commercial use.

Table-2(a): Performance of open plastic solar collectors with air/water heat exchanger (A_c= 10m$^{2)}$

Time (9th May 1985)	temperature difference in air/water heat exchanger (°C)	temperature difference in air/Water heat exchanger (°C)	Mass flow rate of water (Lit/hr)	Isolation (W/m$^{2)}$	Useful energy (Qu)	Thermal Efficiency (%)
13.45	9.2	9.1	240	648	2548	0.393
14.0	7.9	8.9	240	615	1986	0.323
14.15	12.1	8.9	240	799	1492	0.132
14.30	7.9	7.7	240	516	2156	0.418

Table-2(b): Performance of open plastic solar collectors with air/water heat exchanger (A_c= 10m$^{2)}$

Time (10th May 1985)	temperature difference in air/water heat exchanger (°C)	temperature difference in air/Water heat exchanger (°C)	Mass flow rate of water (Lit/hr)	Isolation (W/m$^{2)}$	Useful energy (Qu)	Thermal Efficiency (%)
12.15	11.2	6.0	300	659	2100	0.250
12.30	9.6	5.5	300	817	1925	0.236
12.45	11.5	5.9	300	885	2065	0.233
13.0	10.1	5.7	300	788	1995	0.253
13.15	11.2	6.0	300	844	2100	0.249
13.30	8.4	5.7	300	515	1995	0.347
13.45	6.7	5.3	300	414	1955	0.291

Table-2(c): Performance of open plastic solar collectors with air/water heat exchanger (A_c= 10m$^{2)}$

Time (11th May 1985)	temperature difference in air/water heat exchanger (°C)	temperature difference in air/Water heat exchanger (°C)	Mass flow rate of water (Lit/hr)	Isolation (W/m$^{2)}$	Useful energy (Qu)	Thermal Efficiency (%)
12.15	12.2	6.1	300	846	2085	0.252
12.30	8.7	5.9	300	824	2065	0.251
12.45	9.0	6.0	300	835	2095	0.2504
13.0	9.4	6.0	300	842	2095	0.2488
13.15	9.6	5.9	300	847	2065	0.244
13.30	10.5	6.0	300	846	2100	0.248
13.45	10.7	6.4	300	817	2240	0.274

Table-2(d): Performance of open plastic solar collectors with air/water heat exchanger (A_c= 10m$^{2)}$

Time (12th May 1985)	temperature difference in air/water heat exchanger (°C)	temperature difference in air/Water heat exchanger(°C)	Mass flow rate of water (Lit/hr)	Isolation (W/m$^{2)}$	Useful energy (Qu)	Thermal Efficiency(%)
12.0	12.7	8.8	325	916	3326	0.363
12.15	13.5	6.3	325	911	2381	0.261
12.30	14.3	6.4	325	909	2419	0.266
12.45	13.4	6.5	325	890	2457	0.276
13.0	13.1	6.5	325	858	2457	0.286
13.15	12.9	6.5	325	853	2457	0.288
13.30	12.6	6.4	325	801	2419	0.292

Table:2(e): Performance of open plastic solar collectors with air/water heat exchanger (A_c= 10m$^{2)}$

Time (13th May 1985)	temperature difference in air/water heat exchanger (°C)	temperature difference in air/Water heat exchanger(°C)	Mass flow rate of water (Lit/hr)	Isolation (W/m$^{2)}$	Useful energy (Qu)	Thermal Efficiency (%)
12.0	14.2	8.8	300	886	3080	0.348
12.15	13.1	6.5	300	852	2275	0.267
12.30	13.0	6.9	300	647	2415	0.373
12.45	9.2	5.5	300	605	1925	0.318
13.0	11.6	7.0	300	677	2450	0.362
13.15	11.1	7.4	300	695	2590	0.373
13.30	12.7	8.0	300	834	2800	0.336
13.45	12.6	8.4	300	816	2940	0.360

For the parameters of the experiment and theoretically calculated values from developed model are given in table-2(b) respectively along with the corresponding experimental results choosing. From the table-2(a) to table-2(e) that the system has an efficiency with comparable with efficiencies of conventional solar water heating systems.

It is therefore vast potential for further developments of such systems and subsequent commercialization. Table-2(f) to table-2 (i) also shows that experimental results for porous absorbers which are fairly close to the theoretically calculated values.

Table-2 (f): Experimental and theoretical calculated values model of air water temperature differences from developed thermal using various values of solar radiation

S.No	Isolation (W/m$^{2)}$	Ambient Temperature (°C)	Water Temperature difference Exp (°C)	Water Temperature difference Theory(°C)	Air Temperature difference Exp (°C)	Air Temperature difference Theory (°C)	useful energy during (Exp) kWh	Thermal Efficiency (Exp)
1	610	35.6	7.5	6.9	6.1	7.0	2129	0.3490
2	675	36.5	8.5	7.7	6.9	7.5	2408	0.35674
3	710	38.0	9.2	8.4	7.4	8.3	2582.8	0.3638
4	740	36.9	9.9	9.1	7.9	8.1	2757.3	0.3726
5	525	36.4	8.9	8.2	5.8	6.0	2024.4	0.3856
6	460	36.3	7.8	6.7	4.6	6.36	1605.5	0.3490
7	285	34.5	5.6	4.9	2.1	3.35	732.96	0.2572
8	350	35.5	5.7	5.1	2.5	4.5	872.57	0.2493
9	450	36.2	6.7	5.9	3.5	5.1	1221.6	0.2715
10	960	38.4	9.0	8.3	7.8	9.94	2722.41	0.2836
11	800	38.5	10.2	9.3	7.2	8.24	2513.0	0.3141
12	825	38.2	6.9	6.1	9.8	9.18	3420.5	0.4146
13	840	38.1	6.0	5.3	11.2	9.5	3909.10	0.4654
14	820	37.6	5.5	6.2	9.6	9.2	3211.05	0.3959
15	885	38.1	5.9	6.4	11.5	9.1	4013.81	0.4535
16	790	38.2	5.7	6.3	11.2	9.8	3909.10	0.4948
17	845	39.1	6.0	6.5	8.4	7.4	2931.83	0.3470
18	675	38.9	5.7	5.6	6.7	6.5	2338.5	0.3465
19	475	38.7	5.3	4.9	6.6	6.4	2303.6	0.4850
20	455	38.7	6.2	5.8	7.1	7.4	2478.1	0.5450

Table-2(g): Performance of open loop plastic porous air heating solar collectors using with air/water heat exchanger (A_c= 10m$^{2)}$

Time	$T_a(t)$ (°C)	Ti(t)	$T_w(t)$ Theort. (°C)	$T_w(t)$ Exp. (°C)	Temp Difference(ΔT_f) Theort. (°C)	Temp Difference(ΔTw) Exp. (°C)	$I_t(t)$ Watt/m^2	Q_u (t) kW	$Q_{incident}$ (t) kW	Thermal Efficiency (%)
8.0	26.5	28.0	41.5	41.0	13.5	13.0	60.5	0.57486	1.3815	41.61
8.30	28.0	29.5	43.1	42.9	13.6	13.4	195.1	0.592553	1.4844	39.92
9.0	28.7	30.2	45.0	44.3	14.8	14.1	240.5	0.62350	1.621	38.47
9.30	29.8	31.3	46.4	46.0	15.1	14.7	485.7	0.650	1.757	36.995
10.0	30.4	31.9	47.3	47.1	15.4	15.2	513.8	0.672144	1.8411	36.51
10.30	30.9	32.4	48.2	47.9	15.8	15.5	522.6	0.68541	1.8666	36.72
11.0	31.5	33.0	49.5	49.0	16.5	16.0	650.8	0.7075	1.9521	36.245

11.30	32.0	33.5	52.5	52.3	19.0	18.8	595.5	0.831336	1.7865	46.540
12.0	32.5	34.0	53.6	53.4	19.6	19.4	719.5	0.857868	2.1573	39.766
12.30	33.3	34.8	57.2	57.0	22.4	22.2	668.8	0.981684	2.0061	48.935
13.0	33.6	35.1	59.3	59.2	24.2	24.1	603.5	1.065702	1.8102	58.872
13.30	33.8	35.3	61.0	61.1	25.7	25.8	675.6	1.140876	2.0268	56.295
14.0	33.9	35.4	61.0	61.4	25.6	26.0	670.5	1.14972	2.0115	57.157
14.30	34.1	35.6	60.1	61.3	25.5	25.4	635.5	1.12761	1.9065	59.150
15.0	34.0	35.5	60.7	60.6	25.2	25.1	560.0	1.114344	1.6803	66.320
15.30	33.6	35.1	60.0	59.9	24.9	24.8	527.5	1.10108	1.5822	69.592
16.0	33.3	34.8	58.2	58.1	23.4	23.3	498.5	1.03475	1.4952	69.205
16.30	32.6	34.1	55.3	55.3	21.2	21.0	467.4	0.937464	1.4019	66.871
17.0	31.9	33.4	54.1	53.9	20.7	20.5	313.5	0.915354	1.3302	68.8133
17.3	30.9	32.4	50.6	50.4	18.2	18.0	202.4	0.80480	1.2069	66.684
18.0	29.5	31.0	47.0	46.7	16.0	15.7	89.9	0.70752	1.1667	60.643

Table-2(h) : Performance of open plastic solar collectors with air/water heat exchanger (A_c= 10m$^{2)}$

Time	Inlet temperature (°C)	Isolation (W/m$^{2)}$	Theoretical Water temperature difference (°C)	Experimental Water temperature difference (°C)	Theoretical air temperature difference (°C)	Experimental air temperature difference (°C)	Thermal Efficiency (%)
9.0	19.2	245	0.0	0.0	0.0	0.0	0.0
9.15	19.4	430.	1.5	1.2	1.6	1.4	13.64
9.30	19.6	445	3.5	3.1	3.7	3.5	30.75
9.45	19.8	509	5.8	5.5	5.9	5.4	44.55
10.0	20.0	545	6.8	6.0	6.7	6.0	48.77
10.15	20.1	610	7.1	7.5	7.1	6.1	40.6
10.3	21.2	673	7.5	8.5	7.5	6.9	40.28
10.45	22.3	707	8.3	7.2	8.3	7.4	41.07
11.0	24.2	737	8.1	9.9	8.1	7.9	38.2
11.15	25.7	523	9.0	8.9	6.0	5.8	40.15
11.30	26.8	457	7.9	7.8	5.0	4.6	41.0
11.45	27.8	284	5.7	5.6	3.3	3.2	41.3
12.0	28.0	349	5.6	5.7	3.1	2.9	41.6
12.15	28.5	450	6.9	6.7	4.1	3.9	39.9
12.30	28.7	960	9.4	9.0	9.9	9.8	36.2
12.45	29.2	800	9.3	10.2	8.2	8.25	36.0
13.0	29.6	825	7.1	6.9	9.2	9.8	38.9
13.15	29.4	839	6.5	6.0	9.5	11.2	39.6
13.30	29.8	817	6.2	5.5	9.2	9.6	39.5
13.45	30.0	885	6.0	5.9	9.5	10.5	39.27
14.0	29.8	788	5.8	5.7	9.9	10.1	40.16
14.15	29.6	885	6.0	5.9	9.5	10.5	39.27
14.30	29.8	788	5.8	5.7	9.9	10.1	40.16
14.45	29.6	885	6.1	6.0	9.9	10.2	30.7
15.0	29.4	575	6.1	6.0	9.9	11.2	45.2
15.15	29.2	475	6.5	5.3	6.5	6.7	48.0
15.30	29.1	454	5.8	6.2	4.85	4.9	45.1
15.45	28.9	430	4.0	3.8	4.3	4.2	36.36
16.0	28.7	395	2.5	2.3	2.8	2.6	24.74
16.15	28.5	355	2.2	2.1	2.5	2.3	24.22
16.30	28.3	225	0.5	0.2	1.5	1.2	8.069
16.45	28.1	295	0.0	0.0	0.5	0.2	0.0
17.0	27.8	150	0.0	0.0	0.0	0.0	0.0

The performance of open-loop plastic porous air heating solar collectors with air/water heat exchangers (Ac = 10m²) is presented in Tables 2(g) and 2(h), which record hourly measurements from 9:00 AM to 6:00 PM. These tables provide detailed data on key performance indicators, including air and water temperature differences, solar radiation, useful energy (Qu), and thermal efficiency. The temperature difference across the air/water heat exchanger plays a critical role in determining heat transfer efficiency. As the day progresses, both theoretical and experimental temperature differences increase, indicating that the system efficiently absorbs solar energy. For example, at 9:30 AM, the temperature difference in the water side (ΔTw) is 14.1°C, and it peaks at 25.8°C by 1:30 PM, reflecting improved heat transfer as solar radiation intensifies. Thermal efficiency, a key performance metric, fluctuates between 41.61% at 8:00 AM and reaches a peak of 69.6% at 3:30 PM, showing optimal performance during midday. This suggests that the system operates most efficiently when solar radiation is at its highest. Useful energy (Qu) increases as the temperature difference grows, with a maximum recorded value of 2.1573 kW at 12:00 PM. The data from Table 2(h) corroborates this trend, with solar radiation reaching 960 W/m² at 12:30 PM. The thermal efficiency in this table reaches 48% at 3:15 PM, further supporting the system's effectiveness during peak sunlight hours. Overall, the results demonstrate that the system performs well under optimal solar conditions and has potential for further development and commercialization.

Table-2 (i): Experimental and theoretical calculated values model of air water temperature differences from developed thermal using various values of solar radiation

S.No	Isolation (W/m$^{2)}$	Ambient Temperature (°C)	Water Temperature difference Exp (°C)	Ambient Temperature difference Theory (°C)	Ambient Temperature difference Exp (°C)	Ambient Temperature difference Theory (°C)	Thermal Efficiency (%)
1	610	35.6	6.8	6.0	6.7	6.0	43.5
2	673	36.5	7.1	7.5	7.1	6.1	41.24
3	707	38.0	7.5	8.5	7.5	6.9	40.28
4	737	36.9	8.3	7.2	8.3	7.4	41.07
5	523	36.4	8.1	9.9	8.1	7.9	38.2
6	457	36.3	9.0	8.9	6.0	5.8	40.15
7	284	34.5	7.9	7.8	5.0	4.6	41.0
8	349	35.5	5.7	5.6	3.3	3.2	41.3
9	449	36.2	5.6	5.7	3.1	2.9	41.6
10	961	38.4	6.9	6.7	4.1	3.9	39.9
11	801	38.5	9.4	9.0	9.9	9.8	36.2
12	825	38.2	9.3	10.2	8.2	8.25	36.0
13	839	38.1	7.1	6.9	9.2	9.8	38.9
14	817	37.6	6.5	6.0	9.5	11.2	39.6
15	885	38.1	6.2	5.5	9.2	9.6	39.5
16	788	38.2	6.0	5.9	9.5	10.5	39.27
17	844	29.1	5.8	5.7	9.9	10.1	40.16
18	675	38.9	6.0	5.9	9.5	10.5	39.27
19	474	38.7	5.8	5.7	9.9	10.1	40.16
20	454	38.7	6.1	6.0	9.9	10.2	30.7

The theory therefore can easily be applied for predicting thermal performances of such systems for different climatic region and system thermal efficiency comes out to be 0.337 as shown in table-3a respectively.

Table-3(a): Daily average efficiency of open loop solar water heating system using Air/water heat exchanger connected with plastic air heating collector

S.No	Date	Daily Average incident energy during experiment in kWh	Daily Average useful energy during experiment in kWh	Thermal Efficiency
1	9th May 1985	07.59	2.56	0.337
2	10th May 1985	17.25	4.5	0.261
3	11th May 1985	18.79	4.73	0.252
4	12th May 1985	19.35	5.4	0.279
5	13th May 1985	16.31	5.46	0.235

The performance of the closed-loop system was evaluated using a hot water storage tank with a capacity of 360 liters for experimental measurements. The time-dependent variation in water temperature, both experimentally obtained and theoretically calculated, showed excellent agreement, as presented in Tables 3(b) and 3(c). These results were recorded when no water was withdrawn on the first and second days. The system's performance under different water withdrawal conditions is detailed in Table 3(d), where the theoretical results closely matched the experimental measurements. This comparison indicates that the system performs efficiently under varying conditions, with the experimental data confirming the accuracy of the theoretical model.

Table-3(b) Performance Parameters for solar water heating systems using low-cost plastic air heating collectors for indian climatic conditions

Time (hr)	$I_t(t)$ (W/m^2)	Ambient Temp. (°C)	Water Temp. (°C) Theory	Water Temp. (°C) Exp.	Air outlet Temp. (°C) ($Ta_1(t)$)	Air inlet Temp. ($Ta_2(t)$)
7AM	84.0	22.3	22.5	22.1	26	27
8	257	24.2	23.5	23.4	31	35
9	349	25.7	25	24.7	38	40
10	457	26.8	28	27.6	45	59
11	575	27.8	31	30.5	49	53
12	673	28.0	34.	33.5	53.0	56.5
13	707	28.5	37.5	36.1	50.5	52.5
14	637	28.7	40.0	39.5	42.5	43.0
15	510	29.2	42.5	41.5	32.0	31.9
16	473	29.6	45.0	44.7	30.0	31.5
17	150	29.4	45.5	44.4	29.8	30.7
18	0.0	29.3	44.5	44.3	29.7	30.4
19	0.0	29.2	43.5	44.2	29.6	29.8
20	0.0	28.9	42.5	42.1	29.4	29.0

In the next days water was withdrawal and also in the next days.

Table-3(c) Thermal performance of solar water heating systems using low-cost plastic air heating collectors for indian climatic conditions in a closed loop cycle

Time (hr)	$I_t(t)$ (W/m^2)	Ambient Temp. (°C)	Water Temp. (°C) Theory	Water Temp. (°C) Exp.
7AM	72.0	22.5	40.5	40.5
8	252	24.0	41.3	41.2
9	337	25.3	44.5	44.3
10	452	26.5	47.3	47.1
11	571	27.4	51.0	50.5
12	670	27.9	54.3	53.9
13	701	28.3	57.5	56.9
14	635	28.6	60.0	59.5
15	509	29.0	42.5	41.5
16	433	29.5	45.0	44.7
17	110	29.3	45.5	44.4
18	10.0	29.1	44.5	44.3
19	0.0	28.9	43.5	44.2
20	0.0	28.3	42.5	42.1

Table-3(d) Thermal performance of solar water heating systems using low-cost plastic air heating collectors for indian climatic conditions in a closed loop cycle

Time (hr)	$I_t(t)$ (W/m^2)	Ambient Temp. (°C)	With drawal Hot Water Temp. (°C) (IInd day)	With drawal Hot Water Temp. (°C) (IIIrd day)
7AM	72.0	22.5	29.1	27.8
8	252	24.0	29.9	28.6
9	337	25.3	31.6	30.1
10	452	26.5	32.2	31.5
11	571	27.4	35.9	35.3
12	670	27.9	37.2	37.1
13	701	28.3	38.8	38.6
14	635	28.6	38.9	38.8
15	509	29.0	39.2	39.1
16	433	29.5	39.0	38.9
17	110	29.3	38.8	38.2
18	10.0	29.1	38.5	37.9
19	0.0	28.9	38.1	37.3
20	0.0	28.3	37.5	36.5

Table-3(e): Load profile hot water withdrawal per day (400 Litres)

S.No	Time	Hot water withdrawal (Litres)
1	6.AM-7.AM	10
2	7.AM-8.AM	48
3	8.AM-9.AM	72
4	9.AM-10.AM	60
5	10.AM-11.AM	06
6	11.AM-12.(Noon)	08
7	12.(Noon) -13.PM	08
8	13.PM-14.PM	08
9	14.PM-15.PM	08
10	15.PM-16.PM	08
11	16.PM-17.PM	20
12	17.PM-18.PM	24
13	03AM-4AM	40
14	04AM-5AM	40
15	05AM-6AM	40

The solar water heating systems are shown to provide hot water nearly every day for ten family members in Indian climatic conditions [5]. The results of the above experiment are also utilized in proving the validity of the derived performance equation of HWB type also shows the variation of thermal efficiency with the parameters. The measurements nearly fit a straight line and a least square fit of the measured data yields the rating values of performance parameters for solar hot water system using low-cost plastic collectors are also given in Table-4(a) and table-4(b) respectively.

Table-4(a) Performance Parameters for solar water heating systems using low-cost plastic air heating collectors for indian climatic conditions

System	Type	$F'(\tau\alpha)_e$	$F'U_L$ (W/m^2°C)
Open loop cycle	Porous type absorber	0.720	5.334
Open loop cycle	Porous type absorber	0.720	5.275
Open loop cycle	Porous type absorber	0.720	5.199
Open loop cycle	Porous type absorber	0.720	5.0704
Open loop cycle	Porous type absorber	0.720	5.053
Open loop cycle	Porous type absorber	0.720	4.706
Open loop cycle	Porous type absorber	0.720	4.6064
Open loop cycle	Porous type absorber	0.720	4.235
Open loop cycle	Porous type absorber	0.720	3.2287
Open loop cycle	Porous type absorber	0.720	3.7895
Open loop cycle	Porous type absorber	0.720	3.845
Open loop cycle	Porous type absorber	0.720	3.664
Open loop cycle	Porous type absorber	0.720	3.840
Open loop cycle	Porous type absorber	0.720	3.497

Table-4(b) Performance Parameters for solar water heating systems using low-cost plastic air heating collectors for indian climatic conditions

System	Type	$F'(\tau\alpha)_e$	$F'U_L$ ($W/m^{2o}C$)
Open loop cycle	Non-porous type absorber	0.720	8.5714
Open loop cycle	Non-porous type absorber	0.720	9.2903
Open loop cycle	Non-porous type absorber	0.720	8.7219
Open loop cycle	Non-porous type absorber	0.720	7.869
Open loop cycle	Non-porous type absorber	0.720	8.2285
Open loop cycle	Non-porous type absorber	0.720	8.5714
Open loop cycle	Non-porous type absorber	0.720	8.7273
Closed loop cycle	Porous type absorber	0.535	3.4967
Closed loop cycle	Porous type absorber	0.535	6.1143
Closed loop cycle	Porous type absorber	0.525	5.847
Closed loop cycle	Porous type absorber	0.525	5.6021
Closed loop cycle	Non-porous type absorber	0.357	9.75
Closed loop cycle	Non-porous type absorber	0.347	9.89
Closed loop cycle	Non-porous type absorber	0.327	9.95
Closed loop cycle	Non-porous type absorber	0.307	9.99

Table-5(a) presents the total cost breakdown for solar water heating systems using plastic collector systems. The table shows the individual costs of various components, including the plastic collector, heat exchanger, insulation, and stand. In the Indian market, the price of the plastic collector is Rs. 6,000 (approximately $80), while the heat exchanger costs Rs. 14,000 (around $190). The insulation required for the system is priced at Rs. 1,000 (roughly $15), and the stand costs Rs. 8,000 (around $110). The total initial investment for the entire system amounts to Rs. 29,000 (approximately $395). This cost reflects a relatively affordable option for solar water heating, making it a cost-effective solution, particularly when compared to conventional systems. In Table-5(b), the total cost breakdown for conventional water heating systems is shown. The conventional system's collector costs Rs. 34,000 (about $450), and the storage tank is priced at Rs. 7,000 (around $95).

Table-5(a): Total cost of solar water heating systems using plastic collector systems

Plastic collector systems	Indian market	Indian market
Price of plastic collector	Rs. 6,000	$ 80
Price of Heat exchanger	Rs. 14,000	$ 190
Price of Insulation	Rs.1000	$ 15
Price of Stand	Rs 8000/	$ 110
Total initial investment	Rs 29000	$ 395

Table-5(b): Total cost of conventional water heating systems

Conventional systems	Indian market	Indian market
Price of collector	Rs.34,000	$ 450
Price of storage tank	Rs. 7,,000	$95
Fixed cost	Rs.11600	$155
Total initial investment	Rs 52600	$ 700

Taking interest rate of 8% and annual maintenance cost as 5% the useful energy has been found by dividing the annual cost with the total useful energy for different years in the both types of systems. It was found that low-cost plastic collectors are more suitable than conventional systems although the life of plastic air heater is half of the conventional water heaters as considered as twenty years.

4. Conclusions

The following conclusions were drawn

- The developed thermal models for open and closed loop cycle solar hot water systems using plastic collectors results fairly matches with experimental measured values.
- The performance parameters obtained from experimental results help for designing hybrid solar hot water systems for different indian climatic conditions
- The solar water heating systems using porous and non-porous absorber with heat exchangers are more suitable than conventional hot water systems

References

[1] R.S. Mishra [1986] investigations in solar hot water systems, Ph.D Thesis, IIT Delhi

[2] Bansal, N. K., Uhlemann, R. and Boettcher, A. (1982b). 'Plastic solar air heaters of a novel design-testing and performance', Jul-1783.

[3] Bansal, N. K, R. Chandra and M.A.S. Malik. (1994). Solar Air Heater, Reviews of Renewable Energy Vol 2. Chapter .

[4] R.S. Mishra, Thermal Analysis of Novel Solar Hot Water Systems using low-cost plastic collectorswith air/water heat exchanger, National Conference of Agricultural Engineers, Junagarh, 1994.

[5] R.S. Mishra, Thermal modelling of Solar Hot Water Systems using low-cost plastic collectorswith air/water heat exchanger, National Conference of Mechanical Engineers, university of Roorkee, 1991.

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