EXPERIMENTAL ANALYSIS OF DISTINCT DESIGN OF A BATCH SOLAR WATER HEATER WITH INTEGRATED COLLECTOR STORAGE SYSTEM

by

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The performance of a new design of batch solar water heater has been studied. In this system, the collector and storage were installed in one unit. Unlike the conventional design consisting of small diameter water tubes, it has a single large diameter drum which serves the dual purpose of absorber tube and storage tank. In principle it is a compound parabolic collector. The drum is sized to have a storage capacity of 100 liter to serve a family of four persons.

The tests were carried out with a single glass cover and two glass covers. The tests were repeated for several days. Performance analysis of the collector has revealed that it has maximum mean daily efficiency with two glass covers as high as 37.2%. The maximum water temperature in the storage tank of 60 °C has been achieved for a clear day operation at an average solar beam radiation level of 680 W/m^2 and ambient temperature of 32 °C. To judge the operating characteristics and to synchronize utility pattern of the collector, the different parameters such as efficiency, mean plate temperature and mass flow rate has been investigated.

Key words: *batch solar water heater, compound parabolic concentrators, integrated collector storage system, thermal performance*

Introduction

The integrated collector storage (ICS) systems are simple type solar water heaters that can be used for the supply of hot water for domestic purposes, as alternative devices to the well known flat plate thermosiphonic units (FPTU). These systems consist of one or more water storage tanks which performs dual function of absorbing solar radiation and preserving heat of water. Flat type water storage tanks are cheaper but less effective than tubular storage tanks as the later are water pressure resistant, suitable for direct connection to the water mains and can be effectively used in combination with curved reflectors. Thermal protection of storage tanks is less effective in ICS systems compared to FPTU systems and several methods are suggested to keep water temperature at a satisfactory level. Among them, the use of a selective absorber that reduces radiation thermal losses and double glazing, transparent insulation and inverted or evacuated absorber to suppress convection ther-

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mal losses, are suggested methods that preserve water storage heat. Although ICS systems are considered economical compared to FPTU systems, they are less widespread and must be improved in design and thermal performance in order to become widely applied. In the literature, few works are referred to ICS systems with cylindrical water storage tanks mounted in curved reflector troughs [1-4]. The use of compound parabolic collector (CPC) symmetric reflectors can result in ICS solar systems with effective water heating by using the non-uniform distribution of solar radiation on the cylindrical absorber surface [5]. In most of the above systems the part of the cylindrical absorber is thermally insulated in order to reduce storage tank thermal losses. Considering that ICS systems aim to cover domestic needs of about 100-200 liter per day, the aperture area of each ICS unit can be up to about 2.0-2.5 m^2 which corresponds to use of cylindrical storage tank with diameter 0.2 m to about 0.4 m. The CPC reflectors provide effective solar radiation concentration, depending on their acceptance angle and truncation level [6].

In the present work the experimental study of the distinct design of the batch solar water heater (BSWH) consisting of ICS system with single storage tank as an absorber mounting inside curved reflector trough has been carried out. The freezing of liquid in the conventional tubular type ICS systems is avoided due to single storage tank. This ICS type BSWH of 100 liter per day capacity is designed to cater the need of 4 person family in the Asian countries where the temperature drop during night is relatively less. In this design the thermal insulation on storage tank is not provided to lower down the cost of BSWH and for its wide applications in domestic sector. The paper is focused on the performance analysis of the designed BSWH with single glass cover system (BSWH-1) and double glass cover system (BSWH-2).

Design concepts of the BSWH

Solar water heating system of this type defer to flat plate solar collector in design and operation as it consists of an unit with dual operation, to absorb solar radiation and to preserve the solar heat, instead of the absorbing solar radiation and the heating only of the circulating fluid. BSWH units are thicker solar devices compared to flat plate collectors due to storage tank that is mounted on system trough.

The conventional CPC solar collector, conduction thermal losses can be avoided by using a gap of a few millimeters between a small diameter of tubular absorber and the reflector, but the optical losses of the collector are increased [7]. In the proposed BSWH the gap between the absorber and the reflector has less significance, as it is too small compared with the diameter of the cylindrical storage tank. The designed model for experimentation is shown in fig. 1.

The storage tank painted black is so positioned that its periphery lies on the focus of the parabolic reflector. The reflector is made of stainless steel of 18 gauge. The entire assembly is housed on wooden cradle (Phenol bonded plywood) and supported with circular clamps. The glass wool insulating material was used between the wooden cradle and stainless steel reflector. Non return valve was fitted at the inlet line and air vent, pressure relief valve at the outlet line. For analysis and testing purpose, Al-Cr thermocouples were located

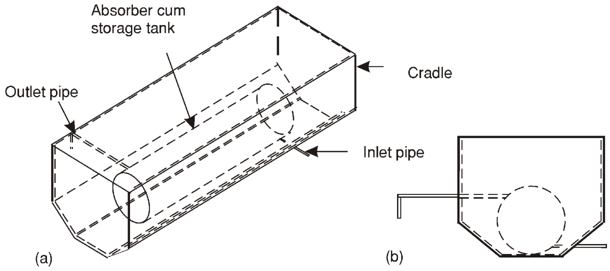

Figure 1
(a) model of BSWH system, (b) cross section model of BSWH system

at different positions in the heater. This type of compact solar water heater is simple in design, low in cost, easy in operation and maintenance, easy to install and of high efficiency compared to flat plate collectors and tubular type ICS systems.

Table 1. Design and construction parameters of the BSWH system

$W\alpha$ [m]	$A\alpha$ [m^2]	Ar [m^2]	C	Ds [m]	V_T [m^3]
0.585	1.1466	1.196	0.9586	0.457	0.1

The storage tank has an entrance for the water at the bottom of one side of it and an exit at the top of the other side of it. The BSWH inlet is connected directly to the overhead or supply tank and its outlet is regulated by the valve. It is naturally circulated type water heater. The storage tank is hydraulically tested for a fluid of 6 kgf/cm^2. The collector is so designed with a large acceptance angle of 180° and low geometrical concentration ratio of 0.9586 which virtually minimizes the requirement of tracking [15].

Testing procedure

The site for testing the performance of BSWH is selected to avoid shading during sunshine hours. The BSWH systems was installed on the testing field of renewable energy park SSGM college of engineering, Shegaon, India (20.7° N, 76.8° E), facing south with slope of 36° and long axis in the east-west direction. The experimental program is being undertaken in two stages. The first outdoor tests as recommended by ISO 9459-2 [8] have been conducted under clear sky day during winter season. In order to evaluate the daily energy gain in the system, the tank is charged at the start of the day and then left to operate during the day without any loads applied. At the end of the day the useful accumulated energy and the temperature of the water in the tank was measured.

The second test was conducted as per the procedure of ISO 9459-3 [9] to monitor the parameters namely daily thermal energy delivery (load), bulk mean delivery temperature, daily irradiation on the collector and ambient temperature.

The effects of single glass cover and double glass cover on the performance of BSWH in terms of mean daily thermal efficiency, overall loss coefficient during night with varying mass flow rates of water have been investigated. The mass flow rate of water, the fluid temperature rise between the collector inlet and outlet, and the solar insolation falling on the plane of the collector on four successive days, were measured simultaneously under steady-state conditions.

The useful heat gained by the water is calculated by the equation:

$$q_{\mathrm{u}} = \mathrm{Fr}\,(\,W\alpha - Do)L\alpha[S - \frac{U_1}{C}(T_{\mathrm{wi}} - T_{\mathrm{a}})] \tag{1}$$

and the instantaneous collection efficiency is calculated on the basis of beam radiation alone with the following equation [10-14]

$$\eta \quad \frac{q_u}{I_b R_b W\alpha L\alpha} \tag{2}$$

Results and discussions

The results of the few characteristic experiments among the plenty of the conducted tests have been presented as below.

Mean daily efficiency

The experimental results of the tested BSWH-1 and BSWH -2 systems regarding their mean daily efficiency as a function of the operating conditions expressed by the ratio $\Delta T_{\mathrm{mD}}/I_{\mathrm{b}}$ (in $\mathrm{m^2K/W}$) are shown in fig. 2. These tests have been conducted with mean wind speed up to 3 m/s and on the basis of beam radiation as diffused radiation are neglected. It has been observed the mean daily efficiency calculated on the basis of effective aperture area, decreases linearly with the increase of operating parameter $\Delta T_{\mathrm{mD}}/I_{\mathrm{b}}$. The results of mean daily efficiency for both the systems studied are shown in tab. 2 in the form of linear equations.

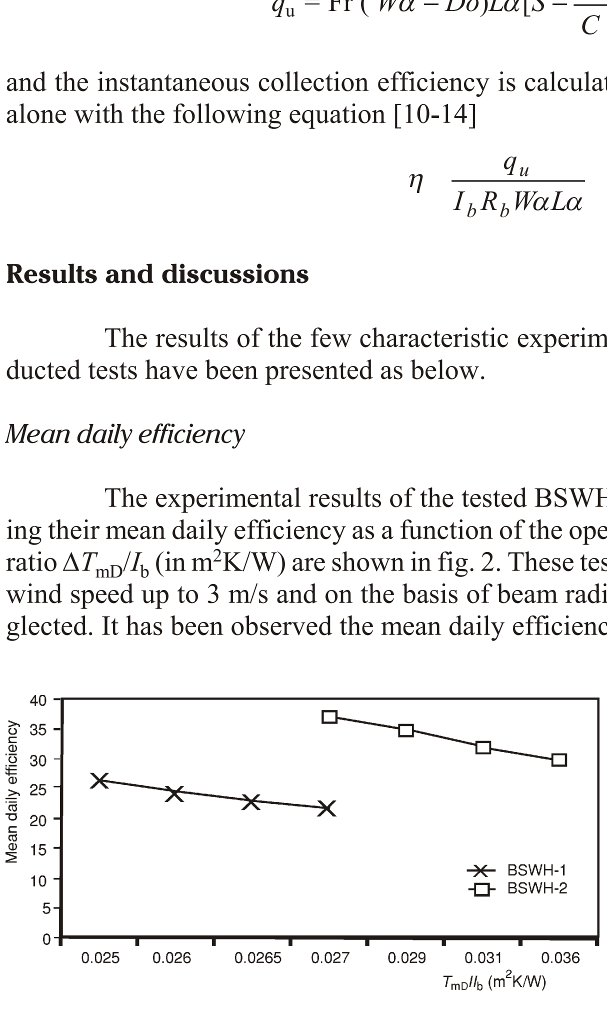

Figure 2. Mean daily efficiency of the studied BSWH system

The diagrams of fig. 2 as well as the equations in tab. 2 show that the BSWH-2 system present higher values of mean daily efficiency compared to BSWH-1 system. The maximum mean daily efficiency is found to be 37.2% for BSWH-2 system whereas for BSWH-1, it is 26.5%. As the number of glass covers increases, the values of transmissivity-absorptivity product for beam radiation $(\Gamma\alpha)$b decreases, hence the flux absorbed in the absorber increases this ultimately causes the value of top loss coefficient and hence the heat loss to decrease.

Table 2. Mean daily efficiency

System	Mean daily efficiency
BSWH-1	$\eta_d = 28 - 1.59\ \Delta T_{mD}/I_b$
BSWH-2	$\eta_d = 47.36 - 2.52\ \Delta T_{mD}/I_b$

Effect of mass flow rate

The effect of mass flow rate on the useful heat gain is shown in fig. 3. The mass flow rate is varied with the increment of 1.5 kg/s on four successive days for both the systems. The slope of the useful heat gain curve goes on decreasing with increasing in the mass flow rate and that the value of useful heat gain q_u tends to some asymptotic value. The increase in the q_u is due to increase in the inside heat transfer coefficient. It is also noted that as the solar flux increases the useful heat gain increases for both the systems. For the BSWH-2 system the higher useful heat gain was obtained at 3 p. m. compared to BSWH-1 system.

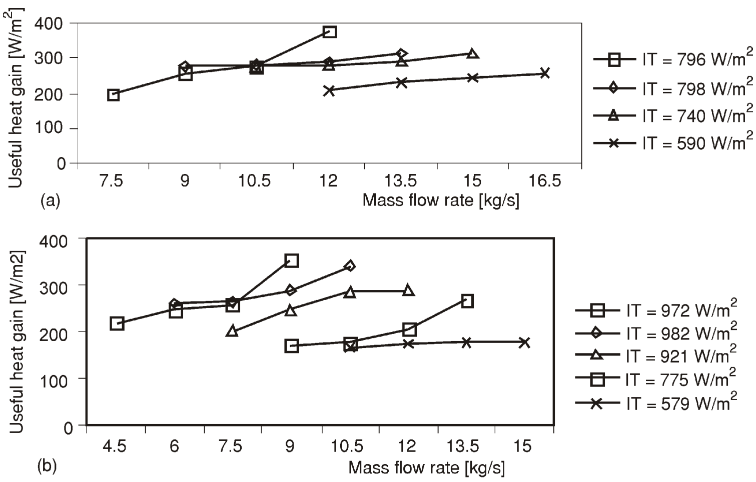

Figure 3. Effect of mass flow rate on useful heat gain
(a) BSWH-2
(b) BSWH-1
(IT – insolation on tilted plane)

Thermal performance during the night

The experimental results of the tested BSWH-1 and BSWH-2 systems regarding their thermal losses during the night are shown in fig. 4, expressed by the coefficient of thermal loss U_l (in W/m^{2}K) as a function of the temperature difference $T_{pm} - T_{am}$ (in K). The results are shown in tab. 3 in the form of equations. Comparing the performance of the BSWH-1 and BSWH-2 of the studied system it is noticed that for BSWH-2 system the average thermal loss coefficient during night is less compared to BSWH-1. It is found that for both the systems thermal losses are significant which is due to the fact that no thermal insulation is provided on the absorber. To overcome this problem both the systems may be thermally protected by selective coatings to achieve effective water heat preservation during the night. Additionally anti-reflection and long wavelength infrared reflecting coatings can be applied to glass cover in order to effectively change the refractive index of the outermost surface in contact with air, thereby reducing the thermal losses.

It can be estimated that the BSWH-2 system combined with a selective coatings could be considered an optimum integrated collector storage system for efficient operation during the night and day.

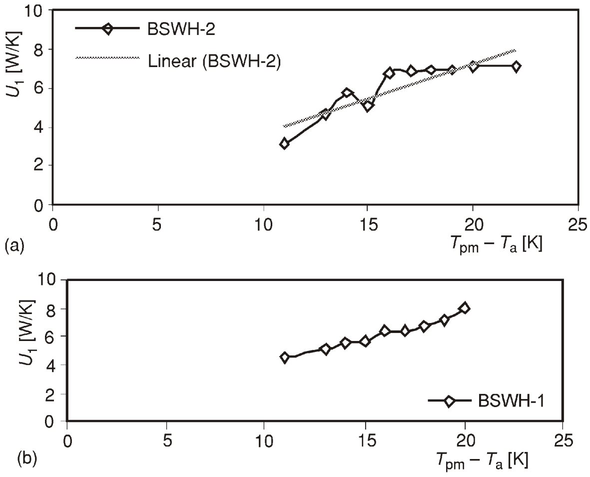

Figure 4. Thermal performance during night
(a) BSWH-2; (b) thermal performance during night (BSWH-1)

Table 3. Thermal loss coefficient during night

System	Thermal loss coefficient
BSWH-1	$U_l = 0.4968 + 0.3582\ \Delta T_{mN}$
BSWH-2	$U_l = 0.1757 + 0.3549\ \Delta T_{mN}$

Variation of water temperature

The hourly variations of water temperatures recorded for BSWH-2 system on a typical winter day are shown in fig. 5.

The maximum water temperature is reached at about 3 p. m. to 60 °C and the average temperature was in between 45-50 °C. After night cooling the storage water temperature recorded at 23 °C at 6.00 a. m. next day which was about 16 °C higher than the tap water temperature.

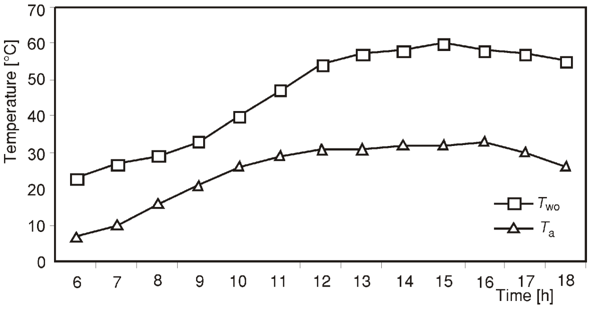

Figure 5. Diurnal variation of water temperatures (BSWH-2)

Conclusions

The experimental investigation of BSWH systems revealed that the maximum operating efficiency is achieved with two glass cover (BSWH-2) system. The maximum mean daily efficiency obtained is 37.2% during 3 to 4 p. m. To achieve the maximum system performance water utility pattern should be such that maximum water is consumed before noon hours. The design is competent to deliver warm water even the next morning.

A BSWH is simple passive system with one storage tank cum absorber without thermal insulation, is inexpensive and have less maintenance cost and installation cost as minimum plumbing skill is required. Because of the use of a single drum unlike large number of small tubes in conventional ICS type the system as a whole operates at lower temperature which reduces the overall convective and radiative losses and results in increase in useful heat gain. Additionally the problem of freezing in tubular ICS is eliminated from the present design. This system does not require tracking owing to its large acceptance angle. This domestic BSWH system with a capacity of 100 liter per day is capable of achieving significant energy savings in hot climate countries particularly in the present situation of acute energy shortage and most suitable to cater the needs of a family of four persons.

Nomenclature

Ar	– absorber (receiver) surface area, [$\mathrm{m^2}$]
$A\alpha$	– aperture area of system, [$\mathrm{m^2}$]
C	– concentration ratio, [–]
Do	– outside diameter of storage tank (absorber), [m]
Ds	– BSWH system depth, [m]
Fr	– heat removal factor, [–]
I_b	– incident beam radiation, [$\mathrm{Wm^{-2}}$]
$L\alpha$	– system aperture length, [m]
q_u	– useful heat gain, [$\mathrm{Wm^{-2}}$]
R_b	– tilt factor for beam radiation, [–]
S	– solar flux, [$\mathrm{Wm^{-2}}$]
T_a	– ambient temperature, [°C]
T_pm	– absorber mean temperature, [°C]
ΔT_mD	– mean water temperature difference during the day, [°C, K]
DT_mN	– mean water temperature difference during the night, [°C, K]
T_wi	– water inlet temperature, [°C]
T_wo	– water outlet temperature, [°C]
U_l	– overall loss coefficient, [$\mathrm{WK^{-1}m^{-2}}$]
V_T	– storage tank volume, [l, $\mathrm{m^3}$]
$W\alpha$	– BSWH system aperture width, [m]
η	– thermal efficiency, [%]

Subscripts

b	– beam radiation
d	– daily
D	– day
i	– inlet
m	– mean
N	– night
o	– outlet

Suffix

α	– absorber

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