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# Experimental investigation and comparison between an integrated compound parabolic domestic solar water heater with and without an air gap introduced at the arms of the CPC

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**Abstract**

The introduction of a concentrator in a domestic solar water heating system is not yet commercialized but research studies have been carried out and model validation done with symmetrical and asymmetrical type of reflectors. With concentrating collectors it becomes imperative to track the sun. Now the method of tracking to be adopted and the number of adjustments required depends upon the collection efficiency and its application. However for households, systems operating at the lower temperature range the optical system best suited are the compound parabolic concentrator. The advantage is that it has large acceptance angle and therefore requires only occasional tracking. The model studied is batch type heater, as the receiver serves the dual purpose of absorber and storage tank, unlike conventional design which consist of a large number of smaller diameter tubes and separate storage tank. The concentrator i.e. the reflector in this case, is supported on a wooden cradle which comprises the two parabolas of the compound parabolic concentrator. In the present work experimental studies have been carried out and mean collector efficiency computed on model with an air gap introduced in the side walls (arms of the CPC) and performance compared with the model without an air gap. This work is built on a model but without the air gap. Results have shown that there is 37.7% percentage increase in collector collection efficiency with air gap.

## 1. Introduction

The batch solar water heater (BSWH) also referred as the integrated collector system (ICS) is simple in design and being naturally circulated type operates at overhead tank pressure. It requires minimum plumbing work and eliminates the use of temperature and differential controllers unlike the conventional flat plate collector systems. Also it brings down the cost of the system considerably due to the absence of a separate storage tank.

However, such systems suffer from thermal energy losses especially during night periods and during insufficient radiation as the absorber and the storage tank constitute a single unit. The thermal protection of the water storage tank is somewhat difficult as a significant part of the external surface is used for the absorption of solar radiation contrary to that of the FPC systems, where the hot water is stored in a separate storage tank which is thermally insulated. Apart from the use of using good insulation, Chaurasia and John Twidell [1] carried out studies to measure overall loss coefficient with simple glass glazing and with the use of transparent insulation material (TIM). Similar work was carried by Reddy and Kaushika [2] to find the effect of using TIM and varying its configuration within the collector. Shridhar and Reddy designed and developed a modified cuboid solar integrated-collector-storage (ICS) system with [TIM] transparent insulation material [3] to minimize the nocturnal heat losses. The use of Phase change material (PCM) was made by Abdul Jabbar Khalifa et al. [4] in Domestic solar water heating systems which resulted in increase in plate temperature and better heat storage during off-sunshine hours. Hailliot..D et al. [5] evaluated the potential of compressed expanded natural graphite (CENG) and (PCM) composites to improve the performance of solar domestic hot water (SDHW) systems. Stratification increases the performance of solar systems. Carrilleo and Cejudo[6] used TRNSYS software to study a model, an indirect solar domestic hot water system with horizontal storage and a mantle heat exchanger.

High solar fraction and higher temperatures can be attained by use of reflectors. Extensive study on domestic use of solar water heaters with stationary concentrating reflectors has been performed by Tripanagnostopoulos and Yianoulis [7, 8], presenting a new concept on ICS systems. Helal.O et al. [9] designed an ICS solar water heater based on three parabolic sections. The performance of the system is modelled by a simulation program written in MATLAB programming language and the results compared with the symmetric and asymmetric CPC reflectors of Tripanagnostopoulos model. Senthilkumar and Yasodha developed a three dimensional compound parabolic concentrator, with the CPC reflectors fabricated as horizontal segments instead of vertical segments. [10] Surface errors were thus reduced and optical efficiency increased. Performance study on an ICS with single tube involute reflector was done by Schmidt and Goetzberger [11]. Such reflector has an acceptance angle of 180°. However in each case positioning of tank becomes cumbersome. Thermal performance of CPC with large acceptance angle has been studied by Jaji Varghese et al. [12] with mean daily efficiency of 37% attained. To make it more consumer friendly good thermal heat retention and to suppress nocturnal heat loss is thus an increasingly important entity in BSWH systems.

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## 2. Description of the system

In the present design to minimize the heat losses from the side walls which constitute a major portion of the system compared to its frontal area, an additional thermal resistance is added by introducing an air gap has also shown in the figure1 and system design parameters shown in Table 1.

The profile of the parabolic reflector is made in AUTOCAD and the printout obtained on a flex in 1:1 scale. The profile is then cut on a sheet metal with the help of shearing machine. This template is then used to cut the plywood sheets. For preparation of the wooden cradle two full sheets (8 ft x 4ft) phenol bonded plywood are used. For obtaining the CPC profile the template is superimposed on the plywood and cut made. Three such strips are cut and then interconnected by longitudinal strips. The skeleton of the wooden profile is then backed by supporting frame. The wooden cradle not only supports the reflectors but also plays a vital role being part of the CPC concept. The height of the cradle and its inclination should be such that it should not shadow the drum under any circumstance. The reflector is made of stainless steel of 28 gauges. The reflector is fitted and positioned on the cradle keeping its focal point on the periphery of the tank, the space between reflector and the wooden cradle is filled with glass wool after leaving appropriate space for air gap. The drum 100 LPD capacity to cater to the needs of a family of four is painted black is positioned horizontally such that it periphery lies on the focus of the parabolic reflector and fastened with the help of circular clamps. Two side pieces were cut to complete the box. The front and bottom of the BSWH is also backed by glass wool insulation. At the top of the box is provision for single and double glass covers. The wooden box was then tiled from the base such that the face of the box would make an angle of 28◦ with horizontal (i.e. latitude of Delhi). Three holes are drilled in the plywood one for water inlet and another for outlet and a hole for a overflow pipe. Size of the holes kept sufficient for ¾ inch pipe fittings. Necessary plumbing fittings are then made with a regulating valve at inlet line, a pressure relief valve and a regulating valve at the outlet.

**Fig.1** Parabolic domestic solar water heater

**Table. 1** System Design Parameters

| S.no | Component | Material | Specification | Dimension |
|---|---|---|---|---|
| 1 | **CPC Component**<br>Wooden cradle<br>Reflector | Ply wood Phenol bonded<br>Stainless steel (mirror finish)<br>Gauge 28 | l x b x h in metres<br>Aperture area in m2<br>Concentration Ratio | 1.4m x 0.72m x 0.91m<br>1.008 $m^2$<br>2.06 |
| 2 | **Glass cover** | Clear Float glass | l x b in meters<br>thickness in mm | 1.4 x 0.72m<br>4 mm |
| 3 | **Storage component**<br>Drum cum Absorber | M.S 304 18 Gauge<br>Coating -Black paint nonselective | Capacity in litres | 100 ltrs |
| 4 | **Insulation** | Glass wool | Front wall non-illuminated in m2<br>Side wall in m2<br>Back wall in m2 | 1.04 $m^2$<br>2.56 $m^2$<br>1.35 $m^2$ |
| 5 | **Air gap** | | in mm | 80 mm |

## 3.0 Instrumentation and Measurement

For prediction of thermal performance of the collector the mean collector efficiency collector is computed. The parameters required for measurement are the solar insolation falling on the collector, the average temperature of the drum, the glass surface temperatures and the average side and bottom wall temperatures. To measure the solar radiation falling on the aperture surface, solar power meter [(Additional temperature included error (+/- 0.38 W/m$^2$ / $^o$ C from 25 $^o$ C).] is used. To obtain the surface temperatures, surface thermocouples (J Type) are mounted on the drum and on the top of glass surface. A total of six thermocouples (four on the drum and two on the glass surfaces) are suitably mounted and fixed with the help of aluminium tape. The seventh thermocouple was kept handy so to measure outer wall temperatures at different locations and obtain the average outer wall temperature. The outputs of the thermocouples are obtained on a digital display temperature indicator via a selector switch. The temperature of inlet and outlet water temperatures are measured by a scientific thermometer. The experimental set up is shown in fig.2

## 4. Experimentation and Analysis

The experiments were conducted under clear sky at open ground at Aryabhatt Institute of Technology, Delhi. The tank was charged at 11:00 am and readings taken at half hourly interval till 15:00 pm whereas the earlier study by Jaji Varghese et al. made at Shegaon, Maharashtra, and readings taken at one hour interval till 16:00 hrs. as the focus of study hovered before and after solar noon. The tests have been conducted for the four hour operation without water drawn-off and as recommended by ISO 9459-2 for outdoor tests. The experimental results are presented in Table 2 and graphs representing variation in outlet water temperature, drum (absorber) temperature and outer wall temperature for both models with time

**Fig.2** Experimental set up

A few approximations done for the analysis:

i. Since the objective of the study is comparison between the two models, the heat stored within the walls of the drum is not considered also being the two collectors designed for the same capacity. Only the quantity of heat stored by water is used in the computation of mean collector efficiency.

ii. The models have been tested at different locations and on different days, but for the comparative study the readings when the mean solar radiation incident on the aperture plane on the two models is in close proximity has only been taken into consideration.

iii. As both the models have low concentration ratio, optical losses have not been worked out for the analysis.

For calculation of the mean collector efficiency for the test duration computation is done using the formula

$$\eta_d = \frac{Q_{wd}}{Q_a} \qquad (1)$$

Where $Q_{wd}$ in Joules is the amount of heat quantity of stored water in the drum and $Q_a$ is the solar energy incident on the aperture surface during the four hour duration of experimentation. If $T_i$ is initial temperature of water at the time of charging at 11:00am and $T_f$ is the temperature of water at 3:00 pm, then:

$$Q_{wd} = m_w c_{pw}(T_i - T_f) \qquad (2)$$

Where, $m_w$ is the mass of water in storage cum absorber drum in Kg

The solar energy $Q_a$ in joules intercepted by the aperture surface $A_a$ is determined by the integration of the solar radiation intensity G(t) measured on the aperture plane;

$$Q_a = A_a \int_{t_i}^{t_f} G(t)dt \qquad (3)$$

Now $\int_{t_i}^{t_f} G(t)dt = G_m$ the mean solar radiation for the time period from $t_i$ (11:00am) to $t_f$ (3:00 pm); can also be obtained from the plot (fig.3) and (fig.4) of solar radiation G(t) vs time, and dividing the area under the curve by the time interval Δt will give the mean solar radiation ($G_m$) in $\frac{W}{m^2}$

Thus the mean efficiency $\eta_c = \frac{m_w c_{pw}(T_i - T_f)}{A_a * G_m * \Delta t}$ (4)

**Table.2** Tabulated data for with Air gap Conducted at Aryabhatt Institute of Technology, Delhi, Average wind speed 3.2 m/s

| Time | Solar | Atm. Temp. | Temp. Of Water | Avg. Drum Surface Temp. | Avg.Glass | Outer | |
|---|---|---|---|---|---|---|---|
| | Beam Radiation | $T_{amb}$ $^0C$ | Inlet | Outlet | Surface- | Cover | Wall |
| | W/m$^2$ | | Ti $^0C$ | $T_f$ $^0C$ | TEMP. $^0C$ $T_d$ | TEMP. $^0C$ $T_g$ | TEMP. $^0C$ $T_w$ |
| 11:00 | 697 | 32 | 24 | - | - | - | |
| 11:30 | 725 | 34 | 24 | 26 | 46.7 | 37.5 | 40.7 |
| 12:00 | 672 | 36 | 24 | 32 | 48.3 | 37.5 | 43.7 |
| 12:30 | 678 | 36 | 29 | 38 | 50.3 | 38 | 41.3 |
| 13:00 | 829 | 36 | 29 | 40 | 49.7 | 39 | 49.3 |
| 13:30 | 842 | 35 | 28 | 44 | 50.3 | 40.5 | 54 |
| 14:00 | 694 | 35 | 30 | 47 | 49 | 41.5 | 49.7 |
| 14:30 | 529 | 34 | 30 | 50 | 45.3 | 40 | 47 |
| 15:00 | 485 | 32 | 31 | 53 | 42.7 | 41 | 49.3 |

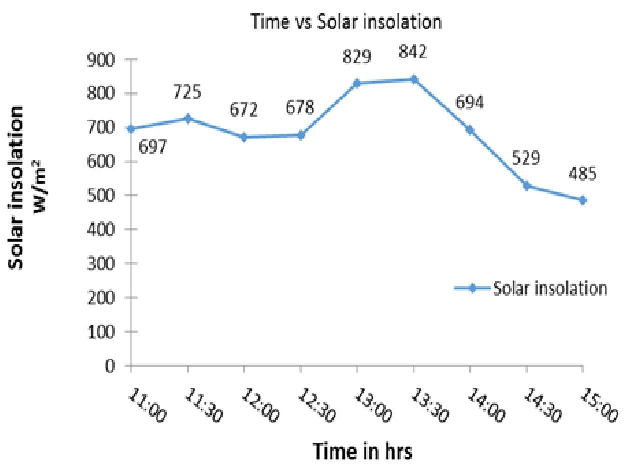


**Fig. 3** ICS with air gap

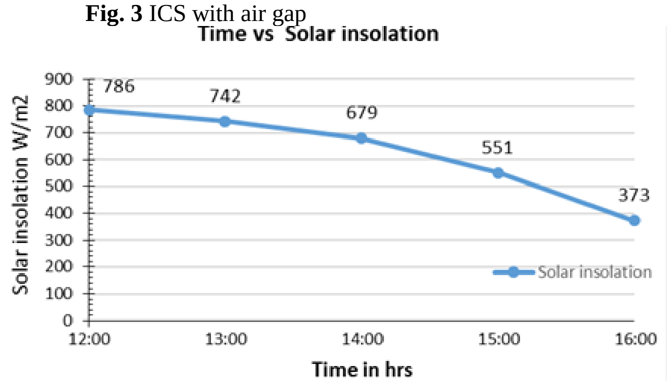


**Fig .4** ICS without air gap

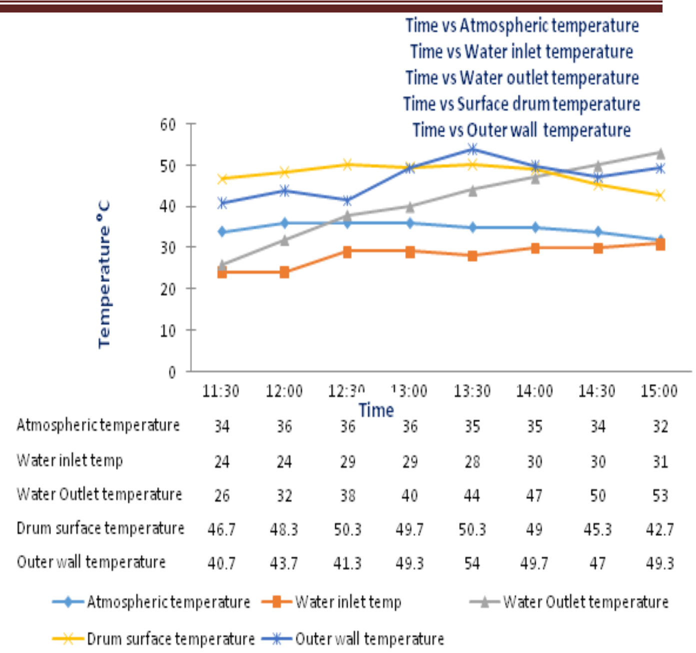


**Fig. 5** ICS with air gap

## 5. Results and discussions

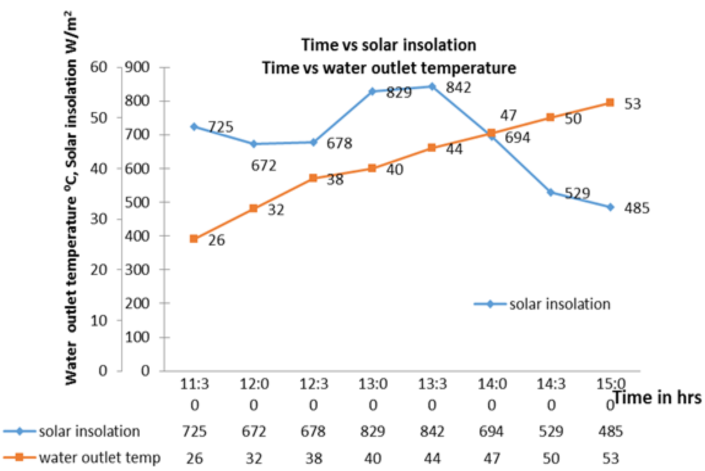


**Fig. 6** ICS with air gap

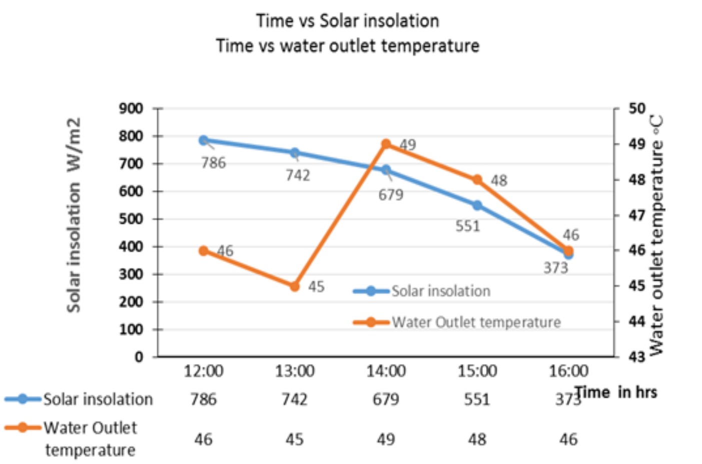


**Fig. 7** ICS Without air gap

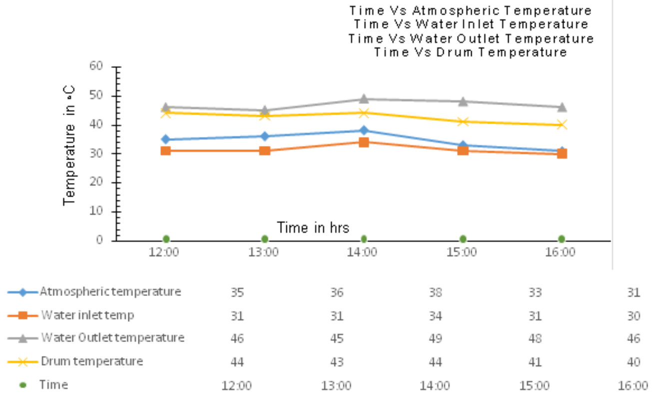


**Fig. 8** ICS without air gap

**(i)** The average temperature of the water goes on increasing although solar insulation decreases after solar noon figure 6 because it is observed that during this period the difference between average drum temperature and outer wall temperature decreases, figure 5 heat loss from collector is reduced and useful heat gain increases whereas as seen in figure7 without air gap there is a continuous drop in temperature after solar noon.

(ii) It is also observed that the difference between average drum temperature and outer wall temperature after solar noon (it was 12:20 at Delhi) from 13:00 pm to 14:30 pm reaches almost an asymptotic value.

(iii) With no water drawn off, the system behaves more as a lumped system, as seen after 14:30 hrs the outer wall temperature is more than drum wall temperature, figure5 the incident flux causes increase in heat gain reflected in the rise in temperature of outlet water, figure 6. In the model without air gap figure 7 and figure 8, the outlet temperature goes on decreasing as solar insulation decreases with time.

(iv) With an additional resistance added in the direction of heat flow attained by slightly modifying the design with no additional cost incurred, the heat loss from the side walls is reduced, the overall heat transfer coefficient $U_l$ decreases and mean collector efficiency increases. Percentage difference in calculated values of overall heat transfer coefficient with and without air gap is 54.7%

(v) The maximum temperature difference of water obtained with air gap is 29$^o$ C and that obtained without air gap is 18$^o$ C,

(vi) The percentage increase in collector efficiency is 37.7% with an air gap introduced on the side walls of the CPC.

## 6.Conclusions

An ICS solar water heater was designed with an air gap introduced at the arms of the CPC so as to suppress the heat loss from the side walls of the solar water heater. Comparative study with a similar model but without air gap has revealed that there is an improvement in the collection efficiency and decrease in the overall heat transfer coefficient. However the study focused only for a short time duration just before and after solar noon and with no water drawn off. Elaborate studies need to be made with different mass flow rates and by varying the inlet temperature for longer duration. But the present study do suggests that the use of air gap can be successfully introduced in ICS solar water heaters and enhance its performance with almost no additional cost incurred by providing a simple modification in the design.

**Nomenclature**

$A_a$ Aperture surface area of the system in m$^2$
$G_m$ Mean solar radiation for the time interval in W/m$^2$
G(t) Solar radiation intensity in W/m$^2$
$Q_a$ The solar energy intercepted by the aperture surface in J
$Q_{wd}$ Amount of heat quantity of stored water in J
$c_{pw}$ Specific heat of water in J/Kg-K
$m_w$ Mass of water in storage cum absorber drum in Kg
$T_i$ Initial temperature of water in $^o$c at the time of charging 11:00 am
$T_f$ Mean final temperature of water at 3:00 pm in $^o$c
$t_i$ Time of start of experiment
$t_f$ Time at the finish of experiment
Δt The time interval between start and finish
$T_{d1}$, $T_{d2}$, $T_{d3}$, $T_{d4}$ Thermocouple probes located on drum
$T_{g1}$, $T_{g2}$ Thermocouple probes located on glass surface
$T_w$ Thermocouple for measuring outside wall temperature
$T_d$ Average drum temperature
$T_w$ Average outer wall temperature
$T_g$ Average glass cover temperature
$\eta_c$ Mean collector efficiency

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