

## An Experimental Study on Solar Flat Plate Collector Using an Alternative Working Fluid

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### ABSTRAK

Makalah ini menghuraikan prestasi pemanas air solar dengan bendalir bekerja alternatif. Pengumpul plat rata solar orientasi yang dipasang telah dibikin dan dihubungkan kepada penukar haba, yang disimpan di dalam tong simpanan air. Pengumpul yang dibangunkan adalah peranti bersuhu rendah yang beroperasi dengan julat suhu ambien sehingga 100°C. Aseton telah dipilih sebagai bendalir bekerja alternatif dan membenarkan untuk sirkulasi semula dalam gelung tertutup. Cangkerang dan penukar haba jenis tiub (tidak bercampur) telah direka dan dibikin untuk pindah haba antara aseton dan air. Intensiti solar meningkat daripada 55 mw/cm<sup>2</sup> pada 8.30 pagi kepada 85 mw/cm<sup>2</sup> pada 1.30 tengah hari dan berkurangan kepada 64 mw/cm<sup>2</sup> pada pukul 5.00 petang. Suhu plat penyerap, yang kekal hampir malar untuk dua jam pertama, meningkat kepada 90°C pada dua jam berikutnya. Ia hampir malar dari pukul 11.00 pagi hingga 1.30 tengah hari dan kemudian turun kepada pada tengah hari. Bendalir panas didapati melepaskan haba kepada air di sekeliling pada kadar malar lebih atau kurang dari pukul 11.30 pagi hingga 5.00 petang. Suhu aseton paling tinggi (72°C) diperhatikan semasa pukul 1.00 tengah hari hingga 2.00 petang. Suhu air meningkat daripada 30°C kepada maksimum 62°C. Keseluruhan keberkesanan sistem tersebut didapati adalah 45% sementara mempertingkatkan input solar kepada haba yang diperolehi oleh air. Bendalir bekerja alternatif seperti aseton, metanol atau etanol mungkin dipertimbangkan untuk menggantikan air dalam pengumpul plat rata memandangkan kepada fakta bahawa bendalir tersebut mempunyai titik didih rendah dikaitkan dengan haba pendam tinggi penyejatan.

### ABSTRACT

This paper describes the performance of a solar water heater with an alternative working fluid. A solar flat plate collector of fixed orientation was fabricated and connected to a heat exchanger, which was kept inside the water storage drum. The developed collector was a low temperature device operating with the temperature range of ambient to 100°C. Acetone was selected as an alternative working fluid and allowed to re-circulate in a closed loop. A shell and tube type heat exchanger (non-mixing) was designed and fabricated for the heat transfer

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between acetone and water. The solar intensity increased from 55 mw/cm<sup>2</sup> at 8.30 am to 85 mw/cm<sup>2</sup> at 1.30 pm and decreased to 64 mw/cm<sup>2</sup> at 5.00 pm. The absorber plate temperature, which remained nearly constant for the first two hours, went up to 90°C in the next two hours. It was nearly constant from 11.00 am to 1.30 pm and then dropped down to 72°C in the afternoon. The hot fluid was found to lose heat to the surrounding water at more or less constant rate from 11.30 am to 5.00 pm. The highest temperature of acetone (70°C) was observed during 1.00 pm to 2.00 pm. The temperature of water increased from 30°C to a maximum of 62°C. Overall efficiency of the system was found to be 45% while considering the solar input to the heat gained by the water. Alternative working fluids such as acetone, methanol or ethanol may be considered for substituting water in the flat plate collector in view of the fact that the fluids have low boiling point coupled with high latent heat of evaporation.

**Keywords:** Solar water heater, alternate working fluid, shell and tube heat exchanger

## INTRODUCTION

A solar water heater utilises helio thermal process method to extract the solar energy. It represents a popular use of solar energy in a mechanically simple system. Solar water heaters are becoming popular because they are affordable and a cheap substitute for other conventional water heating methods. Saiful-Bari (2001) studied the orientations of domestic solar water heaters in Malaysia. The solar collectors in Malaysia are installed on the roof and the slope is almost same as the roof (30 to 40°). It was reported that most collectors in Malaysia were incorrectly installed and were receiving 10-35% less radiation than a properly installed collector, while in some extreme cases, they were receiving as little as 50%. Reddy (1995) conducted a case study on the economical aspects of solar water heaters and electrical water heaters in India. Based on certain conditions, either alternative might be economically advantageous. Hot water at moderate temperature (36 to 58°C) could be obtained in buildings during day time in winter by using reinforced cement concrete slabs or by modifying the roof structure and laying down a net work of aluminum pipes over it, which can offer a low cost passive solar water heating system in the building itself (Chaurasia 2000). In solar dryers using flat plate collectors, the air temperature was in the range of 45.5 to 55.5°C which was suitable for drying most of the agricultural commodities (EL-Sebaili *et al.* 2002).

The performance of the collector increased with the number of glass covers (Felske 1977). Agarwal and Pillai (1982) determined that high conductivity metal powders with suitable binders as bond material between the tubes and absorber plate showed a considerable improvement in the collector efficiency. According to Norton and Probert (1984), single and multi-pass water heaters exhibited similar diurnal heat gain efficiencies at high insolation levels. For lower insolation levels a multi pass unit was found to be more effective. Sorour (1985) studied various designs of continuous and intermittent solar water

heaters and found that a continuous water heater with flow through two transparent perspex sheets and perforated copper plate produced a simple and more efficient collector than the classical design. Qudais *et al.* (2002) compared the performance of a flat plate collector with a convex type collector and found that an additional 45% energy gain was achieved from the convex type over the flat plate collector. A well made solar collector could operate satisfactorily for more than 15 years with minimum maintenance (Rudnich *et al.* 1986).

#### *Phase Changing Fluids*

Generally, water is used as a working fluid for a solar flat plate collector. In a two-phase heat transfer process of a flat plate solar collector with a phase changing fluid, the collector efficiency increased with the fluid mass flow rate (Chandra *et al.* 1983). Bhargava (1983) stated that a water heater based on phase changing materials could provide hot water through out the day if the water pipes were placed near the surface. The efficiency of the system was directly related to the thermal conductivity of the liquid and solid phase of the phase changing material. Prakash *et al.* (1985) investigated the performance of a novel built in storage type water heater containing a layer of paraffin wax as the phase changing material. Water heaters with phase changing material storage at the bottom were more suitable for hot water requirements during off sunshine hours. Yilmaz and Ogulata (1990) used a two-phase solar collector in a water heating system with refrigerant as working fluid. It was claimed that refrigerants could be used with out the risk of freezing, corrosion and fouling. The two-phase collectors could work satisfactorily, if the tank height was greater than half of the collector height. According to Kaushika *et al.* (1982), collector efficiency increased with the increase in liquid length until a point is reached, when the region of super heating causes the vapour to disappear. They also found that the efficiency was high when a heat removal fluid of high latent heat of vaporization was used in the collector. An increase in the saturation temperature of the working fluid in the collector reduced its efficiency. Chun *et al.* (1999) studied the utilisation of heat pipes for solar water heaters and determined that the system performance for different types of working fluid was relatively insensitive to the selection of working fluid. The objective of this study was to identify a suitable alternative working fluid for a solar flat plate collector, which extracts more heat from solar energy, and to study the performance of the water heating system with that fluid.

#### **MATERIALS AND METHODS**

This study was conducted at the department of Bio Energy, College of Agricultural Engineering, Tamilnadu Agricultural University, India. A black painted copper sheet (26 G thickness) with 30 mm insulation (glass wool) was used as an absorber for the solar flat plate collector. The collector outer box was made of plywood. A 3 mm thickness glass cover plate (tuffened glass) was placed on the top of the collector. The specifications of the collector are given

in Table 1 and the side and top views of the over all experimental set up are given in *Figs. 1* and *2*. A heat exchanger was kept inside the water storage drum and connected to the headers in the collector. The outlet coming from the heat exchanger was connected to the bottom header and the top header was connected to the inlet tube of the exchanger. Top and bottom headers were connected by riser pipes. The copper pipes between the collector and water drum were insulated by asbestos rope to avoid heat losses to atmosphere.

TABLE 1  
Dimensions of the flat plate collector

Component	Specification
Collector	
Area	1.7 m <sup>2</sup>
Length	1.7 m
Width	1.0 m
Bottom header	
Material	Copper
Diameter	20 mm
Length	1.0 m
Riser pipes	
Material	Copper
Diameter	13 mm
Length	164 mm
No. of pipes	8
Top header	
Material	Copper
Diameter	20 mm
Length	1.0 m
Inclination of flat plate collector	20° facing south Corrugated, dull black
Absorber plate	painted copper plate (emissivity=0.88)
Number of glass covers	One (3 mm thickness)

#### *Heat Exchanger*

Various types of heat exchangers are available for heat transfer from liquid to liquid. Shell and tube, plate type, U tube and spiral tube are the widely used heat exchangers for commercial applications. The flow path configuration and the mode of heat transfer are different for each model. Yadav and Tiwari (1987) investigated the performance of one pass, double pipe heat exchanger coupled with a flat plate solar collector in both co-current and counter current modes of flow. They found that the temperature of the hot fluid stream decreased with increasing space coordinate along the length of the collectors, but that of the cold fluid was increased, in the parallel flow mode. In the counter flow mode, the temperatures of both fluid streams decreased with the increasing space

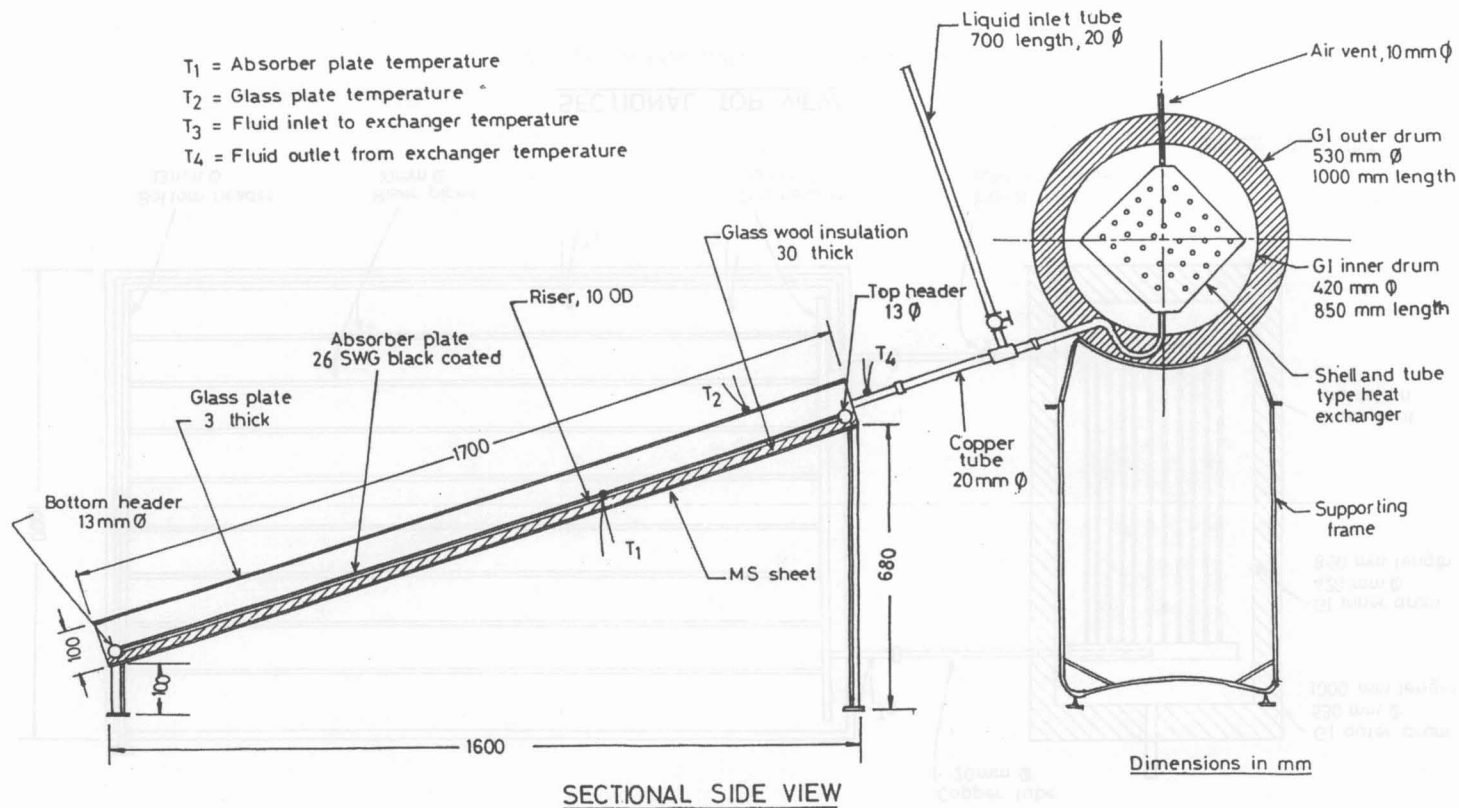


Fig. 1: Flat plate collector cum storage drum

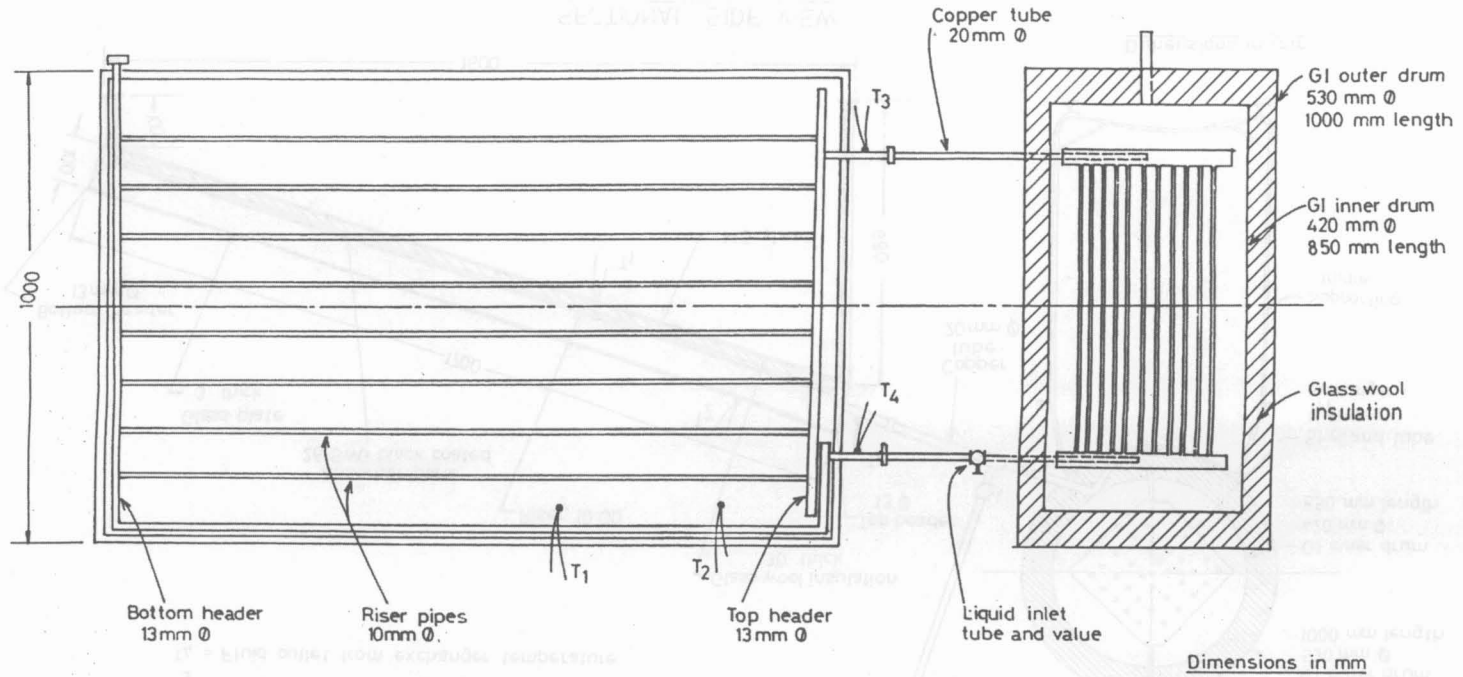
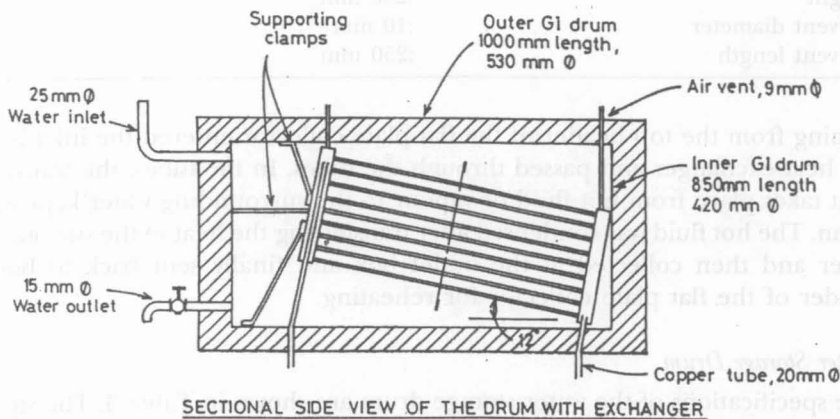


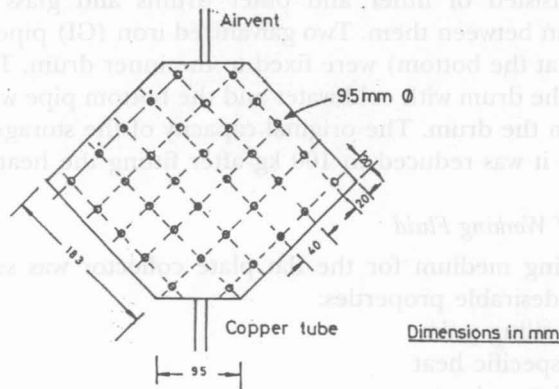
Fig. 2: Flat plate collector cum storage drum

coordinate along the heat exchanger length. As copper is normally used as the riser pipe material in commercial water heaters because of its high thermal conductivity, in our experiment the same material was used for the fabrication of the rest of the parts. A shell and tube type heat exchanger was chosen and it contained three major parts: inlet header box, heat transfer tubes and outlet header box (Fig. 3). Thirty-four copper tubes were provided for fluid passage and the spacing between tubes was kept at 40 mm (centre to centre). The copper tubes were connected to the inlet and outlet header boxes by means of copper gas welding. At the top of the inlet and outlet boxes air vents were provided and the size of the air vent was 9.5 mm outer diameter and 6 mm inner diameter. The exchanger was placed at an inclination of 12° inside an inner drum for easy flow of the fluid from the inlet box to the outlet box. The details of the heat exchanger are given in the Table 2.

A solar flat plate collector of fixed orientation was fabricated and connected to a heat exchanger. The working medium was isolated from the water and was allowed to re-circulate in a closed loop. The hot working fluid or vapour



SECTIONAL SIDE VIEW OF THE DRUM WITH EXCHANGER



SECTIONAL VIEW OF HEAT EXCHANGER

Fig. 3: Heat exchanger

TABLE 2  
Specifications of the developed heat exchanger

Component	Specification
Type	:Shell and tube
Number of tubes	:34
Tube material	:Copper
Diameter	:9.5 mm (OD) 6 mm (ID)
Length	:600 mm
Total surface area	:18000 mm <sup>2</sup>
Capacity of the inlet and outlet boxes with heat transfer tubes	:4.5 lit
Inclination with in the water drum	:12°
<b>Overall size</b>	
Length	:660 mm
Height	:250 mm
Air vent diameter	:10 mm
Air vent length	:250 mm

coming from the top header of the flat plate collector entered the inlet box of the heat exchanger and passed through the tubes. In the tubes, the transfer of heat takes place from hot fluid or vapour to the surrounding water kept in the drum. The hot fluid was condensed after transferring the heat to the surrounding water and then collected at the outlet box and finally sent back to bottom header of the flat plate collector for reheating.

#### *Water Storage Drum*

The specifications of the water storage drum are shown in Table 3. The storage drum consisted of inner and outer drums and glass wool insulation was provided in between them. Two galvanized iron (GI) pipes (one at the top and the other at the bottom) were fixed to the inner drum. The top pipe was used to fill up the drum with cold water and the bottom pipe was used to tap the hot water from the drum. The original capacity of the storage drum was 117 kg of water and it was reduced to 100 kg after fitting the heat exchanger.

#### *Selection of Working Fluid*

The working medium for the flat plate collector was selected based on the following desirable properties:

- i. Low boiling point
- ii. High specific heat
- iii. High latent heat
- iv. Non-corrosiveness for most of the fabrication materials
- v. Wide useful range



TABLE 3  
Dimensions of the water storage drum

Component	Specification
Inner drum	
Material	G.I.Sheet
Length	0.85 m
Diameter	0.42 m
Outer drum	
Material	G.I.Sheet
Length	1.0 m
Diameter	0.53 m

- vi. Easily available in the market and low in cost
- vii. Excellent stability in the working range
- viii. Low freezing temperature
- ix. Should not form scales in the tubes
- x. High thermal conductivity

The following working fluids could be used for the heat pipes:

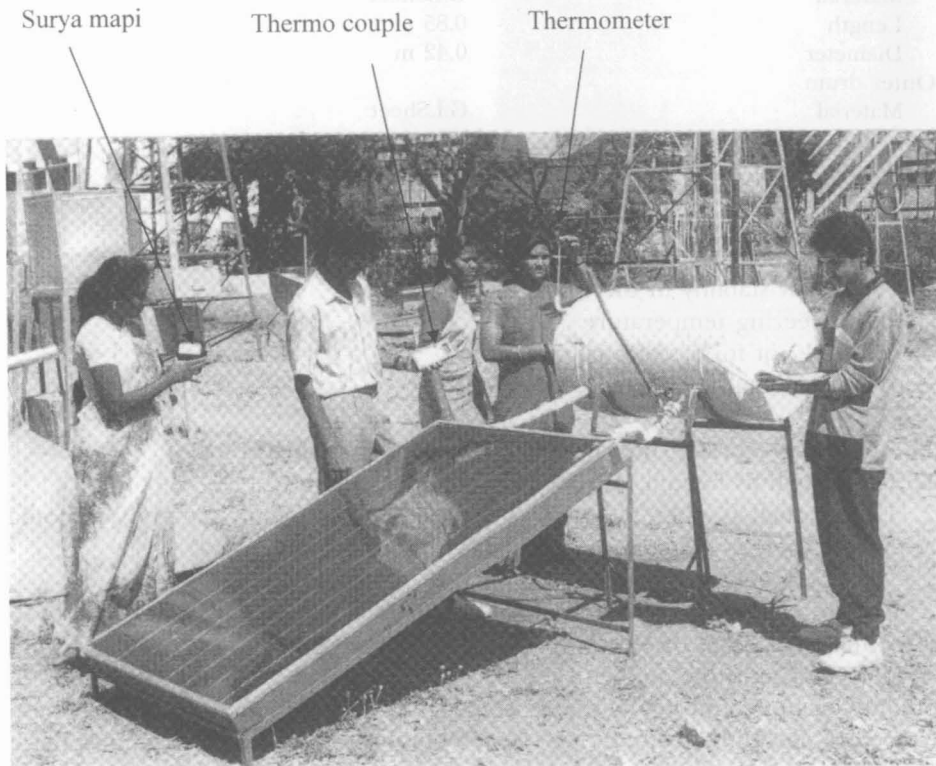
1. Gases such as helium, nitrogen
2. Liquids such as water, methanol, ethanol, acetone, freon, pentane, ammonia
3. Metals such as mercury, potassium, calcium, lithium, silver.

The melting points of different materials ranged from  $-272^{\circ}\text{C}$  for helium to  $96^{\circ}\text{C}$  for silver. For tropical regions, the useful range of the working fluid should be around the ambient temperature. Based on this concept methanol, ethanol, acetone and heptane were selected as suitable medium. Among these four working fluids, acetone has a lower boiling point of  $57^{\circ}\text{C}$  at atmospheric pressure and hence this was chosen as the working medium.

#### *Testing Method and Performance Evaluation*

The flat plate collector was installed on a leveled ground with an inclination of  $20^{\circ}$  facing south. The storage tank was filled with 100 kg of water and the fluid tubes were filled with acetone (commercial grade) through the liquid inlet pipe with the help of a funnel. The liquid was filled up to the top header and the filling tube was plugged. The glass plate was shaded with canvas during filling then exposed to sunlight and the collector was set in operation. Since acetone is inflammable, irritating and easily evaporating fluid, care should be taken while filling the fluid. Acetone vapour coming from the riser tubes was allowed to pass through the heat exchanger, transfer heat to water and condensed back to liquid. Solar insolation ( $\text{mw}/\text{sq.cm.}$ ), absorber plate temperature ( $^{\circ}\text{C}$ ), glass plate temperature ( $^{\circ}\text{C}$ ), acetone inlet to exchanger temperature ( $^{\circ}\text{C}$ ), acetone outlet from exchanger temperature ( $^{\circ}\text{C}$ ), water temperature ( $^{\circ}\text{C}$ ) and ambient temperature ( $^{\circ}\text{C}$ ) were recorded at 30-minute

intervals. Solar insolation was measured by surya mapi (commercially available instrument to measure solar insolation) and water and ambient temperatures were measured by mercury thermometers. All other temperatures were measured by copper constant thermocouples fixed at the respective spots. An overview of the unit with all observation instruments is shown in *Fig. 4*.



*Fig. 4: Overview of the experimental unit with observation instruments*

#### Efficiency Calculation

The efficiency of the flat plate collector with an alternative working fluid was calculated using the heat gained by water with respect to the actual solar energy received by the flat plate collector (Eqn. 1).

$$\text{Overall efficiency of the system} = \frac{\text{heat gained by water}}{\text{input solar energy}} \quad (1)$$

$$\text{Heat gained by the water} = m c_p \Delta T \quad (2)$$

$$\text{Input solar energy (solar energy falling on the collector)} = q A T \quad (3)$$

where

$m$  = weight of water (gram)

$c_p$  = specific heat of water (joule/gram °C)

- $\Delta T$  = temperature difference (outlet temperature–inlet temperature, °C)  
 $q$  = solar insolation (joule/ hour . m<sup>2</sup>)  
 $A$  = area of the collector (m<sup>2</sup>)  
 $T$  = time (hour)

## RESULTS AND DISCUSSION

The flat plate collector developed for this study was a low temperature device operating with the temperature range of ambient to 100°C. It absorbed solar energy consisting of both beam and diffused radiation and transferred heat to the working fluid. The flat plate collector of fixed orientation was selected in view of the fact that the construction is easier, cost is low, requires no tracking, is easy to maintain and is widely available compared to concentrating collectors. Similar type of flat plate collectors are commercially used with water as working fluid for heating water of about 100 litres within a day. This system was modified for indirect heating of water using acetone as working media through a heat exchanger. The performance of the collector with acetone as working fluid was monitored by observing the variations of temperature at different locations and recorded at 30-minute intervals (Table 4).

### *Variation of Ambient Parameters*

Fig. 5 indicates the changes in solar intensity, absorber plate temperature and glass plate temperature of the solar collector with respect to time. It was observed that the solar intensity increased from 55 mw/cm<sup>2</sup> at 8.30 AM to 85 mw/cm<sup>2</sup> at 1.30 PM and decreased to 64 mw/cm<sup>2</sup> at about 5.00 PM. The glass plate temperature was in the range of 38 to 60°C during sunset. It was also noted that the glass plate temperatures closely followed the trend of solar intensity with uniform variation. The absorber plate temperature, which remained nearly constant for the first two hours, went up to 90°C in the next two hours. It remained nearly constant from 11.00 AM to 1.30 PM for a period of three hours and dropped down to 72°C in the afternoon. A difference in temperature of about 24°C was observed over a period of 3½ hours between the absorber plate and glass plate. The increase in the absorber plate temperature from 11.00 AM may be due to the increased solar intensity and the trapping of infrared flux.

### *Variation of Working Fluid Temperature*

Fig. 6 describes the variations in the inlet and outlet temperature of the working fluid. The fluid temperature at inlet to the heat exchanger varied from 38°C at 8.30 AM to about 70°C at 2.00 PM and 52°C at 5.00 PM. The temperature difference between inlet and outlet fluid was 6°C during the start of the trial and it gradually went up to 30°C. The hot fluid was found to loose heat to the surrounding water at more or less constant rate from 11.30 AM till 5.00 PM. The boiling point of acetone was reached after a lapse of about three hours from the start of the trial. It may be inferred that after three hours only acetone

TABLE 4  
Observations on solar flat plate collector with alternate working fluid

Time	Solar insolation mw/cm <sup>2</sup>	Temperature °C					
		Absorber plate	Glass plate	Acetone- inlet	Acetone- outlet	Water- inlet	Water- outlet
8.00	56	40	38	38	32	26	26
8.30	56	40	38	38	32	26	26
9.00	56	40	38	38	34	26	26
9.30	60	52	40	42	36	26	28
10.00	68	60	45	48	36	26	30
10.30	72	65	48	54	36	26	32
11.00	78	88	52	60	36	26	38
11.30	78	90	56	62	40	26	42
12.00	82	90	58	68	40	26	48
12.30	84	90	58	68	42	26	52
1.00	85	93	60	70	43	26	56
1.30	85	93	60	70	43	26	56
2.00	82	93	60	70	43	26	56
2.30	82	90	58	66	38	26	56
3.00	80	88	58	66	36	26	56
3.30	78	85	58	63	36	26	56
4.00	75	80	56	60	32	26	56
4.30	70	80	50	55	30	26	56
5.00	64	72	46	52	30	26	54

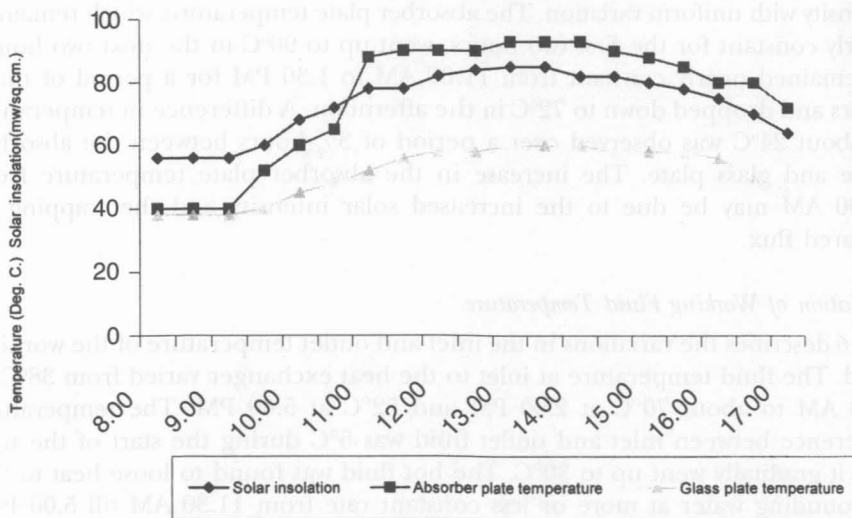


Fig. 5: Variation of solar intensity and temperatures of collector

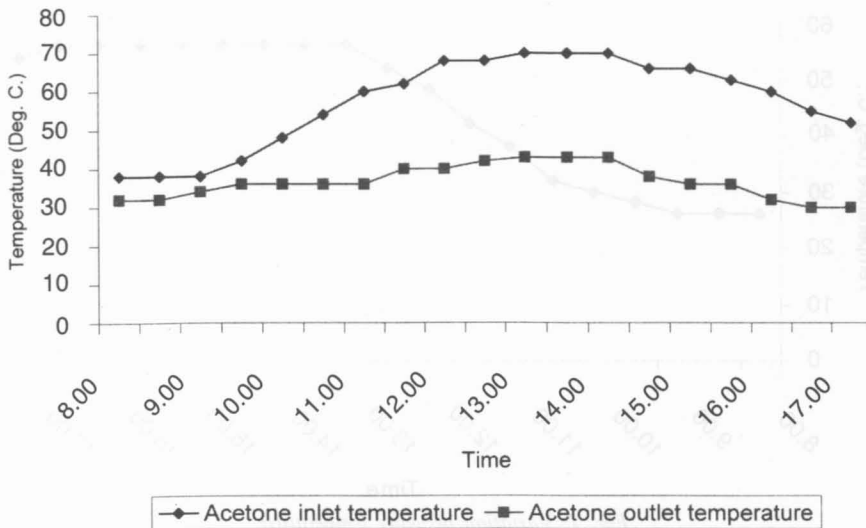


Fig. 6: Variation of working fluid temperature

heated evaporately and the advantage of latent heat of vaporization was realised. This trend is explicitly shown in the temperature variation in Fig. 6. Kaushika *et al.* (1982) also reported that the efficiency of the system was high when a heat removal fluid of high latent heat of vaporisation was used in the collector. It is also inferred that flux of the vaporisation stopped after 4.30 PM due to insufficient solar insolation as evident in the buff fluid inlet temperature. Hence the effective time was only 5½ hours when it was exposed to nearly 9 hours giving an effective exposure time of nearly 50%. The temperature of acetone was maximum (70°C) during 1.00 PM to 2.00 PM and it was not possible to workout the evaporation efficiency due to lack of proper instrumentation facility. Kishore *et al.* (1984) determined that the liquid level was one of the important factors affecting the efficiency of the collector while using phase changing fluids. From the constant temperature profile of both inlet and outlet fluids, the rate of evaporation remained nearly constant due to constant solar insolation. The initial water temperature was 26°C and went up to a maximum of 56°C at 1.00 PM. It remained constant till 4.30 PM and then decreased to 54°C at 5.00 PM (Fig. 7). Hot water with this temperature may be sufficient for domestic use, but for catering applications it may require slightly higher temperature (around 70°C) (Hawladar *et al.* 1984). The temperature of water followed closely the trend of acetone inlet temperature. Bhargava (1983) reported that the water temperature during the evening hours increased with the increase in thermal conductivity solid-liquid phases of the material in a solar water heater with phase changing material.

The overall efficiency of the system was 45% while considering the solar insolation falling on the collector to the heat gained by the water in the storage tank. Chun *et al.* (1999) also achieved the same efficiency while using heat pipes

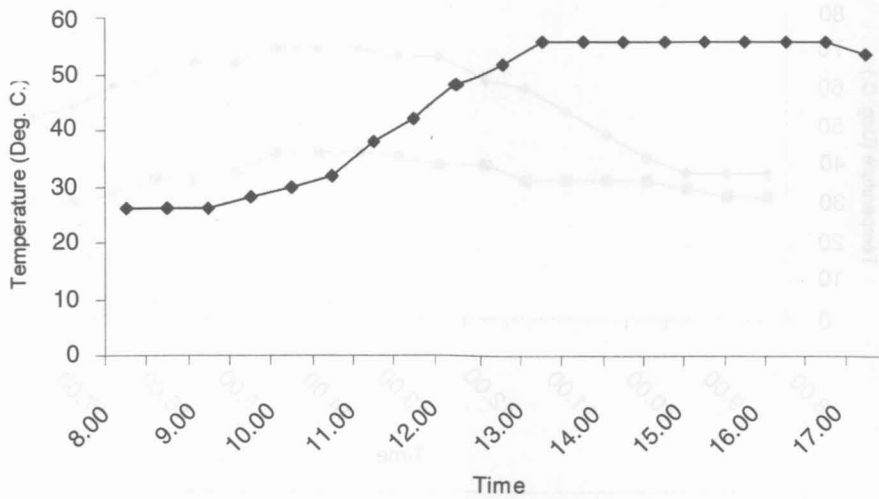


Fig. 7: Variation of water temperature

for solar water heaters. While evaluating the performance of solar water heater with steam cooker, Mahar (1985) achieved an efficiency of 51.5% for solar water heater and 16.1% for solar steam cooker.

### CONCLUSION

Alternative working fluids such as acetone, methanol and ethanol can be considered for substituting water in the flat plate collector in view of the fact that the fluid has low boiling point coupled with high latent heat. However, problems with the handling of the fluid, corrosion of the components and the environment effects have to be kept in mind before choosing an alternative fluid. Careful consideration has to be made in cases where the hot water is used for edible purposes which may be contaminated with diffused working fluid in the heat exchanger due to hairline cracks, pressure build up or due to corroded components. These alternate fluids have potential for further exploration as working fluid instead of water and it is also possible to de-link the flat plate collector from the storage tank.

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