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Domestic Solar Water Heater: Theoretical and Experimental Studies

Y.P. Yadav* and G.N. Tiwari**

Centre for Energy Studies
Indian Institute of Technology, (CESIIT), Delhi,
New Delhi-110 016, India.

ABSTRACT

This paper presents the design and performance of a domestic water heater of hundred litres capacity per day. The system has been tested for a month i.e. from mid-December, 1985 to mid-January, 1986 which is considered to be Delhi's harsh cold period. Furthermore, a thermal modelling of this system has been carried out based on the transient analytical approach. To make a quantitative assessment of the analytical results, numerical calculations have been made for a typical winter day i.e. 13 February, 1986. The analytical results have also been validated by the experimental observations. A good agreement between them has been observed.

INTRODUCTION

Solar water heating systems represent the most common form of utilization of solar energy; however, it is impossible to conduct experiments to determine the performance of these systems under different conditions of atmosphere/temperature and wind velocity/and solar insolation. Hence a mathematical model to predict the performance of a system under a given set of operating conditions (viz. atmospheric, solar and inlet water temperature) is absolutely essential for the design of an efficient and economically viable system. A mathematical model applicable to solar water heating systems operating with the natural circulation of hot water between the collector and the storage tank was presented first by Close (1962). He developed a simple analytical model for predicting the day-time performance of such a system with no hot water withdrawal from the storage tank. He set up a partial differential equation for mean system temperature assuming a sinusoidal variation of solar insolation and ambient temperature. De Sam (1964) generated a lumped parameter heat balance equation to predict the water temperature in a tank without withdrawal, using actual solar radiation data and a half hour time step. Iqbal (1966), on the other hand, studied the effects of free-convection superimposed on forced flow in uniformly heated tubes. A major improvement over Close's model (1962) was made by Gupta and Garg (1968) who incorporated in their analyses system capacity and a collector efficiency factor. They also considered insolation and ambient temperature as Fourier Series in time. Chinnery (1971), through his mathematical model, explained the reverse flow under certain specific conditions but he did not make any prediction of the magnitude of the effect on the system performance.

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*Lecturer, Department of Physics, C.M. Science College, Darbhanga, Bihar
**Assistant Professor in the Centre.

Ong (1974) has further extended the analysis of Close (1962) by incorporating a different formulation of the plate efficiency factor and retaining the assumption of equality of the mean collector and storage temperature; the plate and fin efficiency, plate heat loss coefficient, tube water film heat transfer coefficient friction factor and physical properties of water were taken as appropriate functions of temperature and flow rate of water. Later Ong (1976) improved the analysis by dividing the convective loop into several sections; the energy balance was considered for each of these sections. In both studies (Ong 1974, 1976) Ong predicted and measured the mass flow rate, mean tank temperature, collector efficiency and mean system efficiency. The experimental values for the mean system efficiency was about 1.25 times the efficiency of the simple model. The effect of the collector area, storage tank elevation and solar insolation on the day time behaviour of thermosiphon water heaters was also investigated by Baughn and Dougherty (1977, 1978); while a mathematical model for obtaining the steady state temperature distribution and the flow rate in the thermosiphon system was developed by Zvirin et al. (1977). A parallel plate absorber type solar water heating system was analysed by Grossman et al. (1977) for quasi-steady state conditions with forced and natural circulation of water between the absorber and the storage tank. An analytical and dimensional model for the thermosiphon loop was developed by Zvirin et al. (1978). Essentially linear temperature distribution in both the collector and the tank for no-draw situation was observed by Shitzer et al. (1979) and water flow rate was found to be thirty three per cent lower than the rate predicted theoretically by Zvirin et al. (1978). Daneshyar (1979) used a variation of Close's (1962) analysis to predict the average monthly performance of the system assuming a batch draw at the end of the day and no night losses. The dynamic performance of a thermosiphon solar water heater was also studied by Sheridan et al. (1967) and Klein et al. (1975, 1976, 1980).

A more sophisticated measurement of the thermosiphon flow rate was made by Morrison and Ranatunga (1980a, 1980b). A common thermosiphon solar water heating system without a heat exchanger in the storage tank was studied by Huang (1980) by solving the energy, momentum and continuity equations using the finite difference technique. The same technique was used by Metrol et al. (1981) with a different set of assumptions. Based on the formulation of Ong (1974), Sodha and Tiwari (1981) analysed the performance of a thermosiphon solar water heating system with hot water withdrawal from the storage tank. The performance of the system, incorporating a heat exchanger in the storage tank was also analysed by Sodha et al. (1983); this model has more physical significance than that by Tzafestas et al. (1974) which defines an artificial heat transfer coefficient and makes use of the finite difference method. Norton and Probert (1982) revived the characteristics of thermosiphon flow and the various analytical models describing natural circulation solar water heater behaviours. Further they (Norton and Probert, 1983) also reviewed the conventional methods of accomplishing the thermal rectification, often required in solar water heating systems in order to prevent unwanted heat losses which occur at night as a result of reverse thermosiphonic motions from the store to the solar collector; in addition to this, novel non-return values for this purpose and their potential application have also been described by them. The behaviour of direct thermosiphonic solar water heaters was also studied by Norton and Probert (1984) experimentally for a variety of ambient conditions and vertical heights of the storage tank above the collector; they reported that for high insolation levels, single and multiple pass water heaters exhibit almost similar diurnal gains. Kudish et al. (1985) measured thermosiphon flow rate as a function of thermosiphon head and inlet temperature. Huang and Hsieh (1985) presented a simulation method for a solar thermosiphon collector. To verify this they conducted experiments and showed that the experimental results were in good agreement with the simulation. A study of thermosiphon circulation in solar water heaters incorporating glass tubular evacuated collector and water-in-glass manifold was reported by Harding and Zhiqiang (1985). Tiwari (1985) described the transient performance of a thermosiphon water heating system with n-unit connected in series.

A solar water heater operating under thermosiphon flow could be very useful for domestic purposes as well as for remote areas where the conventional sources of energy e.g. electricity, are difficult to supply. Because of these potential uses it is a field of considerable interest for both individual researchers and various organizations. For example, the Department of Non-Conventional Sources of Energy, Ministry of Energy, Government of India, has tried to popularise this system and gain its acceptance by the people. However, failures in the performance of the system, particularly during harsh cold days, has proved an obstacle. The Delhi Energy Development Agency (DEDA) has reported that the unsatisfactory performance of the existing systems is due to faults in their design. As a result of this a leading manufacturer, Allied Metals and Engineering approached CESIIT to test the performance of a domestic solar water heater and to suggest some modifications of the existing design if necessary. A month long rigorous testing of the system was carried out and a temperature drop of 10-15°C was observed; the reasons being (i) reverse flow occurring during the night, (ii) the storage tank was not at the proper height above the upper header of the collector (Ong, 1974), (iii) short circuiting in the system and (iv) inadequate insulation around the storage tank. All these above shortcomings have been successfully accounted for (Fig. 1) and consequently a modified domestic solar water heater has been proposed and tested (Fig. 2).

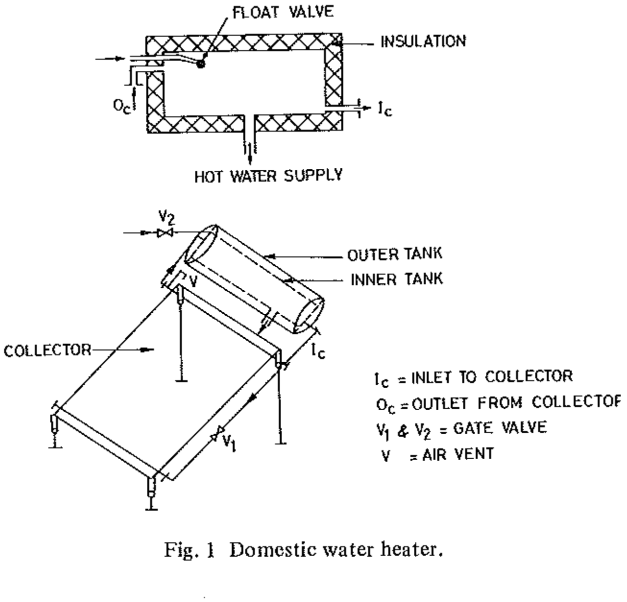

Fig. 1 Domestic water heater.

DESIGN DESCRIPTION

The proposed system basically consists of separate heat collection and storage units, coupled by means of insulated connecting pipes (Fig. 1). Detailed specifications of the system are given in Table 1.

Table 1. System specifications

(A) Collector Specifications

Collector frame	Aluminium section
Gasket	Neoprene rubber gasket
Glazing	Toughened glass 4 mm thick
Glazing transmission	0.66
Collector body	Aluminium extruded section bottom CRC sheet, processed
Bottom insulation	50 mm thick crown-150 fibre glass wool provided as back insulation
Side insulation	25 mm thick crown-300 fibre glass wool provided as side insulation
Absorber plate	0.8 mm thick aluminium sheet
Absorber coating	Nickel black selectively coated
Coating absorptivity	0.92
Coating emissivity	0.25
Riser	Copper tube 12.7 mm outer diameter
Absorber	Aluminium selectively coated
Riser bonding	Mechanically clinched followed by spot welding
Inlet and outlet header	25 mm outer diameter copper pipe
Collector support	M.S. angle and pipe structure

(B) Storage Tank Specifications

Tank material	M.S. 3.15 mm thick
Tank inside coating	Epilux 4 Epoxy base paint
Tank insulation	Mineral wool 150 mm thick
Tank outside cladding	24 G aluminium.

Collection Unit (Flat-Plate Collector)

Type: Copper tube – Aluminium absorber

Absorber area: 2.1 m^2

Absorber Matrix: The absorber consists of ten 12.7 mm outer diameter copper tubes brazed to two 25 mm outer diameter copper pipe header forming the water channel. The copper tubes are spaced at a distance of 120 mm and are in close mechanical contact with the aluminium absorber plate. The absorber is nickel black selectively coated.

Insulation: The absorber panel is thermally insulated from the collector box by the following means:

i) Crown-150 fibre glass wool of 50 mm thickness is provided as back insulation.

ii) Crown-300 fibre glass wool of 25 mm thickness is provided as side insulation.

iii) Radiation reflecting aluminium foil is provided over the insulation.

iv) The inlet and outlet headers are insulated from the collector box and sealed using a high temperature rubber gasket.

v) 4 mm thick toughened glass, used as top glazing for the collector, has a continuous rubber gasket along the edges to provide perfect sealing.

Collector/Housing: The collector box is made up of extruded aluminium sections. The top glazing with rubber gasket is held in position by the top aluminium angle frame using hardened self-tapping sheet metal screws. The inlet and outlet headers have flanges welded to them, ensuring quick and direct inter-connections to the storage tank.

Storage Unit

The storage unit consists of two coaxial cylindrical tanks. The 150 mm annular space between them is filled with mineral wools. The inlet for cold water from the mains is provided with a float valve and a long air cavity insulated tube to add it to the bottom of the tank without mixing with hot water. The valve makes the tank of non-pressure type. There is a provision for withdrawal of hot water from the tank. The set up is shown in Fig. 2.

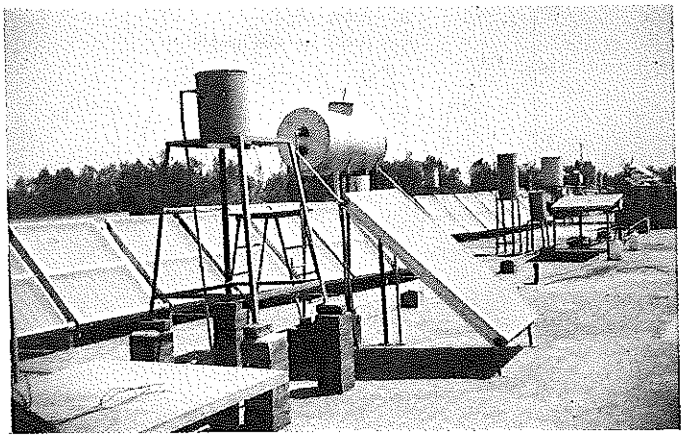

Fig. 2 Set-up of the solar water heater.

EXPERIMENTAL OBSERVATIONS

The experimental studies carried out comprised (i) the month long performance of the system and (ii) the experimental validation of the results of the thermal modelling for a typical day; the details of these studies follow:

Month round performance of the system

The experimental observations were started early in the morning at about 7.00 a.m. and were carried out up to the evening i.e. till sunset. In the morning, at 7.00 a.m., the storage tank was filled with fresh water. The glass cover of the collector was also cleaned daily in the morning before sunrise. The storage tank water temperature was measured by a copper-constantan thermocouple arrangement by placing the thermocouple junction in the middle of the storage tank. This observation was made regularly at intervals of three hours, from 7.00 a.m. to 5.00 p.m. The hot water obtained from the storage tank was used each evening. This study was carried out for a month i.e. from 18th December, 1985 to 16th January, 1986 which is considered to be Delhi's harsh cold period. The results are shown in Fig. 3. The upper, middle and lower curves stand for hot water temperature, maximum ambient temperature and minimum ambient temperature respectively. The points A, B and C on the hot water temperature profile depict the condition of the sky, namely: partly cloudy, cloudy, and cloudy with rainfall respectively. Other points depict an almost clear sky. From the results of this figure (Fig. 3), it is evident that for an almost clear sky, the temperatures of hot water obtained from the system above the maximum and the minimum ambient temperatures are almost 30 and 40°C respectively. On the basis of these results, the earlier design with the modification suggested herein should be suitable for domestic purposes.

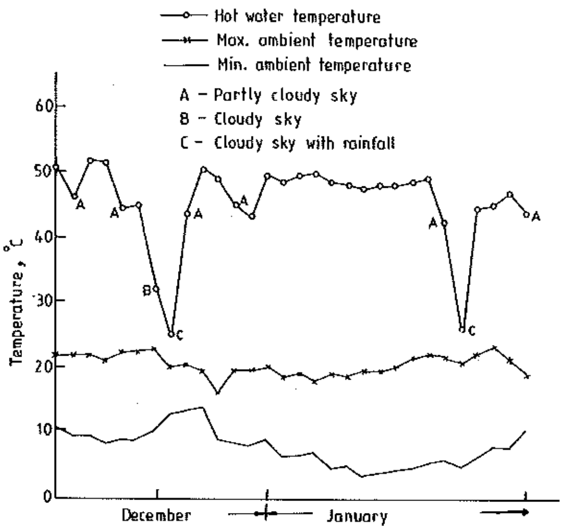

Fig. 3 Daily average hot water temperature of the domestic water heater.

Experimental observations for validation of the results of the thermal modelling

The thermal modelling involves meteorological parameters. The total radiation available on the horizontal surface was measured by a pyranometer-strip-chart recorder arrangement. The measurement of diffuse radiation on the horizontal surface was made by a pyranometer with a shading ring arrangement. The hourly values of the beam radiation on the horizontal surface were then obtained by substracting the values of diffuse radiation from the total radiation. Total solar radiation available on the glass cover of the collector was calculated by putting the values of the beam radiation and diffuse radiation in the Lice and Jordan formula (Duffie and Beckmann, 1980) which was used further in the computation of the analytical results of the thermal modelling of the system. The hourly variations of solar insolation on the horizontal surface and the collector-surface, and the ambient temperature on a typical day i.e. 16 February, 1986, Delhi are shown in Fig. 4. Experimental observations were taken on this typical day from 7.00 a.m. to 7.00 a.m. (next day). In the evening at 5.00 p.m. the gate valve V_1 (Fig. 1) was closed to uncouple the collector from the storage tank; this was done so as to check the night heat losses on account of reverse circulation flow. The water temperature of the storage tank was measured by thermocouple arrangement.

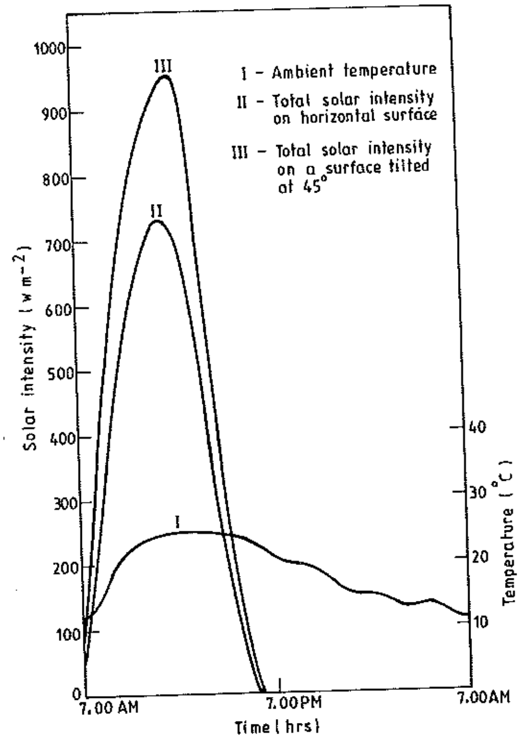

Fig. 4 Hourly variation of solar intensity and the ambient temperature on 13 February 1986.

THERMAL MODELLING

A schematic diagram of the proposed system is shown in Fig. 1. The energy balance at the collector and the storage tank may be expressed respectively as:

Sunshine Hours

Collector (thermosiphon flow)

$$\underset{\text{(Useful energy)}}{\dot{m}_w C_w (T_{wo} - T_{wI})} = \underset{\text{(Available energy)}}{F' A_c H_s (\tau\alpha)} - \underset{\text{(Energy stored)}}{\left(M_{wc} \frac{dT_c}{dt} + M_{wp} \frac{dT_p}{dt}\right)}$$

$$- \underset{\text{(Losses through collector)}}{F' A_c U_c (T_{wc} - T_a)} - \underset{\text{(Losses through connecting pipes)}}{U_p A_p (T_{wp} - T_a)} \qquad (1)$$

Storage tank

$$\dot{m}_w C_w (T_{wo} - T_{wI}) = M_{wt} \frac{dT_t}{dt} + \dot{M}_w C_w (T_{wt} - T_a) + U_t A_t (T_{wt} - T_a) \qquad (2)$$

(Available energy for storage tank)	(Energy stored)	(Losses due to withdrawal of hot water from the storage tank)	(Losses from storage tank to ambient)

Equations (1) and (2) when combined together give the energy balance for the system as a whole,

$$M_{wc} \frac{dT_c}{dt} + M_{wp} \frac{dT_p}{dt} + M_{wt} \frac{dT_t}{dt} + \dot{M}_w C_w (T_{wt} - T_a) + F' A_c U_c (T_{wc} - T_a)$$

$$+ U_p A_p (T_{wp} - T_a) + U_t A_t (T_{wt} - T_a) = F' A_c H_s (\tau\alpha) \qquad (3)$$

Off-sunshine hours

During off-sunshine hours, the collector is uncoupled from the storage tank, hence the energy balance for storage tank takes the form,

$$M_{wt} \frac{dT'_t}{dt} + \dot{M}_w C_w (T'_{wt} - T_a) + U_t A_t (T'_{wt} - T_a) = 0 \qquad (4)$$

According to Gupta and Garg (1968), the body temperature of the collector, connecting pipes and the storage tank are equal to their water temperature. This leads to

$$T_c = T_{wc}; \; T_p = T_{wp}; \; T_t = T_{wt} \qquad (5)$$

Further, on the basis of experimental observations, Close (1962) reported that the mean water temperature in the tank was the same as the mean water temperature in the absorber during the sunshine hours. This will be true for the connecting pipes temperature too. Hence

$$T_w = T_{wc} = T_{wp} = T_{wt} \qquad (6)$$

Similarly during off-sunshine hours

$$T'_w = T'_t = T'_{wt} \qquad (7)$$

Substituting equations (5) and (6) in equation (3), one obtains,

$$\frac{dT_w}{dt} + bT_w = f(t) \qquad (8)$$

where,

$$b = (\dot{M}_w C_w + F' A_c U_c + U_t A_t)/M_S \quad \text{(neglecting pipe losses)}$$

$$M_S = M_{wc} + M_{wp} + M_{wt}$$

$$f(t) = a\, H_s + b\, T_a$$

$$a = F' A_c\, (\tau\alpha)/M_S$$

Substituting equation (7) in equation (4), one gets

$$\frac{dT'_w}{dt} + b'\, T'_w = f'\,(t) \tag{9}$$

where,

$$b' = (M_w C_w + U_t A_t)/M_{wt}$$

$$f'\,(t) = b'\, T_a$$

Initial conditions

So as to solve equations (8) and (9), respectively initial conditions are

$$T_w = T_{wo} \quad \text{at } t = 0 \tag{10}$$

$$T'_w = T'_{wo} \quad \text{at } t = t' \tag{11}$$

where t' refers to the value of t just at the beginning of the off-sunshine hours.

Now equations (8) and (9) subject to the initial conditions (10) and (11) respectively yield,

$$T_w = T_{wo} \exp\,(-bt) + \exp\,(-bt) \int_0^t f(t) \exp(bt) dt \tag{12}$$

and

$$T'_w = T'_{wo} \exp\,(-b'\,\Delta\, t) + \exp\,(-b't) \int_{t'}^{t} f'\,(t) \exp\,(b'\, t) dt \tag{13}$$

where,

$$\Delta\, t = t - t'$$

Expressions (12) and (13) which stand for water temperature during sunshine hours and off-sunshine hours respectively, could also be expressed in terms of Fourier coefficients of solar intensity and ambient temperature as follows:

Periodic behaviour of solar intensity and ambient temperature yields

$$H_S = H_{So} + \sum_{n=1}^{\infty} H_{sn}\, e^{i(nwt - \sigma n)}$$

and
$$T_a = T_{a0} + \sum_{n=1}^{\infty} T_{an}\, e^{i(nwt-\phi_n)} \tag{14}$$

In practice, sufficient accuracy is achieved by terminating the series at $n = 6$, hence

$$H_s = H_{so} + \sum_{n=1}^{6} H_{sn}\, e^{i(nwt-\sigma n)}$$

and
$$T_a = T_{ao} + \sum_{n=1}^{6} T_{an}\, e^{i(nwt-\phi_n)} \tag{15}$$

Substituting equations (14) and (15) in (12) and (13) respectively one obtains,

$$T_w = T_{wo} \exp(-bt) + (\frac{aH_{so} + bT_{ao}}{b}) (1 - \exp(-bt))$$
$$+ \sum_{n=1}^{6} ((\frac{aH_{sn} \exp(-i\,\sigma_n) + b\, T_{an} \exp(-i\phi_n)}{inw + b}) \times (\exp(\text{inwt}) - \exp(-bt))) \tag{16}$$

and
$$T'_w = T_{wo} \exp(-b'\,\Delta t) + T_{ao}\, (1 - \exp(-b'\,\Delta t))$$
$$+ \sum_{n=1}^{6} ((\frac{b'T_{an} \exp(-i\phi_n)}{inw + b'}) (\exp(inwt) - \exp(inwt' - b'\,\Delta t))) \tag{17}$$

In order to appreciate the analytical results obtained so far numerical calculations have been made. Numerical values of the relevant system parameters taken for calculations are as follows:

$\alpha = 0.92$
$\tau = 0.86$
$A_c = 2.1\ \text{m}^2$
$A_t = 1.5\ \text{m}^2$
$F' = 0.77$
$M_S = 6.18 \times 10^5\ \text{J}\ {}^\circ\text{C}^{-1}$
$M_t = 4.21 \times 10^5\ \text{J}\ {}^\circ\text{C}^{-1}$
$U_c = 8.05\ \text{Wm}^{-2}\ {}^\circ\text{C}^{-1}$
$U_t = 0.60\ \text{Wm}^{-2}\ {}^\circ\text{C}^{-1}$

The hourly variation of water temperature, computed from the equations (12/16), (13/17) is shown in Fig. 5. The continuous line represents the theoretical results while the circle represents the experimental one. From this figure, it is obvious that there is a good agreement between the experimental and theoretical results. Other conclusions are the same as reported by Sodha and Tiwari (1981).

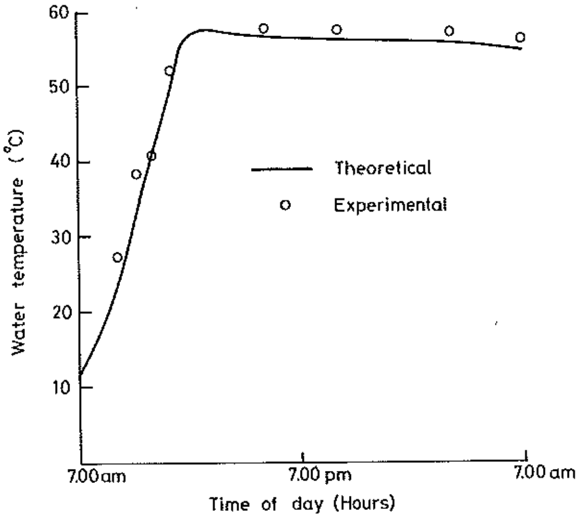

Fig. 5 Hourly variation of water temperature of a domestic solar water heater on 13 February 1986

NOMENCLATURE

A	Area (m^2)
C	Specific heat (J kg^{-1} $°C^{-1}$)
F'	Collector efficiency factor
H	Intensity (Wm^{-2})
$\dot{m}$	thermosiphon mass flow rate (kgs^{-1})
M	Heat capacity (J $°C^{-1}$)
$\dot{M}$	Withdrawal mass flow rate (kgs^{-1})
T	Temperature (°C)
T'	Temperature during off-sunshine hours (°C)
U	Overall loss coefficient (Wm^{-2} $°C^{-1}$)
α	Absorptivity of the collector's absorber
τ	Transmittivity of glazing

Subscript

a	ambient air
c	collector
p	connecting pipes
t	storage tank
s	solar

S	system
w	water
wc	collector and water within it
wp	connecting pipes and water within it
wI	inlet water
wt	storage tank and water within it
wo	outlet water

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