Journal of Scientific & Industrial Research
Vol. 67, July 2008, pp. 549-555

Performance enhancement of natural circulating storage type solar water heaters

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Received 15 December 2006; revised 06 May 2008

Performance of solar water heater was simulated for one extraction per day (at 18:59 h), two extractions per day (12:00 & 18:59 h) and hourly extractions (06:00 - 18:59 h). Annual thermal energy output (for 2 m^2 collector system) was 1181.65, 1354.69 and 1585.89 kWh/m^2/year at annual collector-tank system efficiency of 59.61, 68.34 and 80.0 % respectively. Maximum temperatures reached at 18:59 h was 92.3°C for one extraction mode and 67.1°C for two extraction mode. Performance can be enhanced (20-30%) through multiple extraction of water over the day by controllable dual tank system and a performance optimizer for electrical back up. Also, average solar radiation and weather data of Bangalore for 1977-2005 is presented.

Keywords: Collector efficiency, Electronic control, Flat plate collector, Solar water heater

Introduction

Integration of electronics with solar thermal devices has lead to opportunities for efficiency boosting through matching of load requirements to solar energy input.Optimal parameters[1] for SWHs are as follows: glass covers, 1-3 numbers; pipe spacing, 20-200 mm; pipe diam, 5-15 mm; pipe thickness, 0.7-1.5 mm; distance between cover and absorber, 10-40 mm; cover plate spacing, 10-30 mm; cover plate thickness, 2-6 mm; emittance of cover plate, 0.60-0.65; transmittance of glass cover, 0.80-0.98; absorptance of absorber plate, 0.90-0.99; thermal conductivity of cover, 0.2-1.0 W/mK; thermal resistance of insulation, 0.1-1.0 $W/mK)^{-1}$; and vertical clearance of hot water tank storage above collector, 200-500 mm. Operating boundary conditions for SWH are as follows: global incident solar radiation, 0-1 kW/m^2; wind velocity, 0-8 m/s; sky temperature, 278-293 K; ambient temperature, 10-40°C; relative humidity, 20.0-99.5%; and source water pressure, >130 kPa.

Development-cum-field experience studies[2-4] has evolved an economically optimal configuration as follows: i) Collector [area: 2 m^2, non-tilting, fixed in N-S direction at an angle of (latitude + 15º), which is considered as an optimal tilt for mass installations]; ii) Collector with single glass cover, thermosyphonic natural circulation and all other geometric designs as per standards; and iii) Single horizontal tank (vol, 100 l) placed in North direction. SWHs [three groups- A (90%), B (2%), C (8%)] has following size (collector area) and storage tank capacity, respectively (Table 1): A, 2 m^2, 100 l; B, 1 m^2, 50 l; and C, 2 m^2 , 50 l.

In this paper, performance optimization of solar water heaters (SWHs) through load-source matching using multiple extractions, dual tank systems and programming of electrical back-up during inadequate solar insolation is discussed. Also, development of average global solar radiation data and related average weather data based on 28 year average is presented for Bangalore (Latitude, 12º 58' N; Longitude, 77º 35' E; Elevation, 921 m above mean sea level) because Bangalore has largest number of roof top SWHs installed [~0.6 million m^2 out of total 1.1 million m^2] and SWH manufacturers [~40 out of 85 approved manufacturers] in India.

Experimental Details

Performance Indices

A number of methods are available for performance estimation of SWHs[5-11]. In this paper, energy outputs and efficiencies at hourly intervals were estimated based on Hottel- Whiller-Bliss (H-W-B) equation[10] and summation over the time horizon of interest. This method is simple and accurate [± 5.5% (band width of 11%)][10]. Composite efficiency of collector-storage tank (dimensionless) (H-W-B equation) is generated from a plot of experimental efficiency test readings of the collectors as

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Table 1— Typical specifications of solar water heaters

Sl No.	Particulars	Specifications
1	Collector dimensions	Size, 1860 mm x 1245 mm x 110 mm; Hydraulic test pressure, 1.0 MPa; Weight, 75 kg
2	Absorber panel	
	Fins (10 per m width)	Copper fins TIG welded to tube (122 mm x 1710 mm x 0.20 mm)
	Tubes (10 per m width)	Copper tubes (12.7 ϕ mm x 1716 mm x 0.56 mm)
	Headers (2)	Copper tubes (25.4 ϕ mm x 1295 mm x 0.71 mm); Header end connections (brass flanges, 62 ϕ mm x 4 mm t)
	Absorber panel coating	Selective coating: black chrome graded Al-N (absorptance > 93 %; emittance < 15 %)
3	Collector box	Anodized/power coated extruded Al channel: 1.6 mm thick (gasket sealing box and glazing-EPDM[a] /neoprene; sealing, elastic epoxy compound / silicon sealant)
4	Glazing	Toughened/tempered low iron glass (glass transmittance, > 86 %; glass thickness, 4.0 mm)
5	Thermal insulation	Rock wool (density, 48 kg/m^3; thermal resistance of insulation, 0.48 m^2 °C/W; thickness of insulation for tank and pipe, 100 mm & 50 mm; cladding, polished Al sheet of 0.56 mm thickness)
6	Tank	SS[b] 304 TIG[c] welded (tank capacity, 100 l; thickness, 1.25 mm; hydraulic test pressure, 1.0 Mpa)
7	Pipe and pipe fittings	Galvanized iron piping
8	Source water tank head	> 3.0 m

[a]Ethylene propylene diene monomer, [b]Stainless steel, [c]Tungsten inert gas

$$\eta = A_0 - A_1 \left(\frac{\Delta T}{I}\right) \quad \ldots(1)$$

where A_0 (collector efficiency factor) and A_1 (collector loss coefficient or thermal efficiency factor) are constants, I is global incident solar radiation on collector surface (W/m^2) and ΔT is difference between inlet temp. (T_{in}) and ambient temp. (T_a). For 26 new thermosyphon collectors with storage, typical values of A_0 are 70-85% and A_1 are 7.4-21.2 W/ °C m^2.

For single extraction per day, water T_{in} at 06:00 h is taken as a reasonably good approximation of T_a. For two and multiple extractions, water T_{in} is taken as air T_a. Power output of collector (P_O, kW) is computed using power input (solar radiation input x collector area) (P_I, kW) and H-W-B equation as

$$P_O = P_I \eta \quad \ldots(2)$$

Final water temperature in time period (T_f) is obtained from

$$P_O = \frac{MC_p (T_f - T_i)}{t} \quad \ldots(3)$$

where M is mass of water heated (kg), C_p is specific heat of water, T_i is initial water temperature at start of time period and t is time period (s).

Energy output (E_O) (kWh) for a given time interval is product of power output (P_{oij}) (kW) and time duration (t_{ij}) (h) as

$$E_O = P_{Oij} t_{ij} \quad \ldots(4)$$

Annual energy inputs (E_I, kWh/m^2) and outputs (E_o, kWh/m^2) are computed based on 12 daily data points averaged over the month (for that particular hour) for 12 months (28 years) multiplied by number of days in that month as

$$E_O = \sum_{m=1}^{12} \left[\sum_{j=1}^{12} \sum_{i=1}^{12} P_{oij} t_{ij} \right] d_m \quad \ldots(5)$$

where d_m is number of days in that month.

$$E_I = \sum_{m=1}^{12} \left[\sum_{j=1}^{12} \sum_{i=1}^{12} P_{Iij} t_{ij} \right] d_m \quad \ldots(6)$$

Overnight temperature drop is on account of reverse circulation (12-20 W)[15] and thermal dispersion from tank (15-50 W). In present study, overnight drop is determined by using an experimental curve fit. Hot water is charged into collector tank and temperature drop is computed over the period 18:00 h to 06:00 h next morning. Experiments are conducted for 4 hot water temperature conditions (25°, 45°, 65° and 85°C). Thermal loss varies between 26-71 W. Temperature drops for 4 conditions are curve fitted to give an equation as

$$\Delta T_{drop} = 1.6979 e^{0.2012(T_f)} \; (R^2 = 0.99) \quad \ldots(7)$$

Operating annual energy output ($E_{o,operating}$, kWh/m^2) is obtained by adding augmenting energy source component (LPG or electric power). R^2 is measure of approximation of a curve fit to data points. In present case, electric booster heater fitted inside solar collector tank was used for augmenting solar energy. Operating energy output is given by

$$E_{O,operating} = E_{O,computed} + E_{\mathrm{O,\,electric}} \qquad \ldots(8)$$

Electrical energy gives shortfall in solar collector output to the user's requirement. Typical user's requirement per m^2 of collector area for providing 150 l of hot water heated to 45°C (ΔT = 20ºC) is taken as 3.5 kWh/day (1277.5 kWh/y). Since collector tank size is 50 l/m^2, water is heated to a higher temperature than 45ºC and/or extracted more than once.

Experimental Measurements

Thermal energy change in the tank over a day is determined by a unique microcontroller based thermal energy meter which consists of embedding thermocouples in collector tank (divided into isothermal finite volumes), measuring their temperature in real time and integrating these to estimate energy changes in the tank (since mass of water and specific heat in any volume zone is considered constant). Efficiency plotted versus ($\Delta T/I$) constants A_0 0.80 (range, 0.70 - 0.85) and A_1 5.0 W/m^2 ºC (range, 7.4 - 21.2) to be used in H-W-B equation (for simulating annual performance of collectors) are determined.

Experimental back-up electrical energy for a 2 m^2 collector is under measurement for the past 7 years (2000 till present) using an energy meter (single phase watt-hour meter). However, this parameter must be used with caution because increase in thermal load from design load can be a cause for energizing boosters. Instead, number of cloudy days, on which electrical booster heaters are switched on for at least 50 min (corresponding to minimum energy requirement), is recorded to calculate availability factor.

Results and Discussion

Solar Radiation Weather Data

Mani[12] complied solar energy data and related weather data for Bangalore for 1977-1980. In present paper, global incident solar radiation data for 1977-2005 is computed from experimental meteorological data through statistical data analysis[13] (Table 2).

Solar radiation (Table 3) computed from basic data for the period 06:00 h-18:00 h (06:00 h in January is average for all days of January for all years from 1980-2005). These are 28, 30 or 31 hourly averaged readings (for each day in the month) for a given hour for 28 years. The data for 1977-2005 in comparison with the data for 1977-1980 varies from -5.5% to +3.9% at individual points and by +0.162% for annual value. Rainy season of June-August is characterized by high cloud cover, low air T_a, high wind, high rainfall (though highest rainfall is in October). It is seen that during July-September and November-December, energy input is below 5 kWh/d (Table 4). The period with cloud cover between 6-7 Okta is 123 d/y. The data is not available for cloud cover 7-8 Okta, which could possibly be a better indication of the days, on which electric heaters have to be invoked.

Availability factor (AF, dimensionless) is the ratio of number of days when solar hot water supply is available (min. 50 l/day heated to 40ºC corresponding to an energy output of 0.87 kWh/day) to the number of days in an year as

Table 2 — Annual weather data for Bangalore for 1977-2005

Sl.No.	Parameter	Min.	Max.	Mean	Deviation in individual data points of annual average values [1]		Deviation in mean of annual average values[a]
1	Rainfall, mm	937.5	1251.8	1051.7	-8.6	+9.4	+1.8
2	Relative humidity, %	30.0	95.0	70.46	+3.0	+8.0	+2.0
3	Wind velocity, m/s	1.1	4.5	2.54	+0.2	+0.6	+2.85
4	Ambient air temperature, ºC	16.3	27.7	24.15	-0.1	-0.8	-0.47(1.96 %)
5	Cloud cover, Okta	1.02	8.0	4.4	NA	NA	NA
6	Rainy days/year	69	82	70.2	NA	NA	NA
7	Cloudy days (Mean Okta >7)	38	47	42.3	NA	NA	NA

[a]Deviation of 1977-2005 data as compared to data of 1977-1980 NA, Original data not available for comparison

Table 3 — Solar radiation data for Bangalore for 1977-2005.

Hours→ Months↓	Hourly[a] global incident solar radiation, kWh												
	6	7	8	9	10	11	12	13	14	15	16	17	18
Jan	0.00	0.03	0.20	0.43	0.64	0.78	0.85	0.85	0.76	0.62	0.43	0.23	0.04
Feb	0.00	0.05	0.24	0.46	0.64	0.80	0.84	0.85	0.78	0.65	0.45	0.23	0.05
Mar	0.00	0.07	0.29	0.53	0.73	0.87	0.94	0.92	0.83	0.69	0.49	0.27	0.07
Apr	0.00	0.08	0.30	0.53	0.73	0.86	0.92	0.90	0.83	0.67	0.48	0.25	0.07
May	0.00	0.09	0.28	0.49	0.68	0.82	0.87	0.85	0.78	0.64	0.46	0.26	0.09
Jun	0.00	0.10	0.25	0.44	0.59	0.70	0.74	0.74	0.67	0.55	0.42	0.24	0.09
Jul	0.00	0.07	0.21	0.36	0.47	0.55	0.60	0.60	0.56	0.48	0.34	0.19	0.07
Aug	0.00	0.06	0.19	0.35	0.46	0.55	0.61	0.62	0.57	0.47	0.33	0.19	0.06
Sep	0.00	0.05	0.19	0.37	0.54	0.63	0.68	0.67	0.62	0.50	0.35	0.19	0.06
Oct	0.00	0.04	0.20	0.41	0.54	0.71	0.76	0.76	0.67	0.54	0.37	0.16	0.04
Nov	0.00	0.03	0.16	0.34	0.52	0.64	0.70	0.69	0.61	0.52	0.36	0.18	0.04
Dec	0.00	0.02	0.15	0.33	0.50	0.61	0.66	0.66	0.60	0.48	0.32	0.17	0.03

[a] One hourly interval (i.e. from 06:00 h to 07:00 h, etc.)

Table 4 — Weather data for Bangalore for 1977-2005 (mean values)

	Air temp. °C	Wind velocity m/s	Relative humidity %	Rainfall mm/year	Cloud cover[a]	Global radiation kWh/d	Beam radiation kWh/d	Diffuse radiation kWh/d
Jan	21.8	2.6	65	0.8	2.9	5.8615	1.4110	4.4505
Feb	24	2.3	64	11.1	2.6	6.0455	1.8658	4.1797
Mar	26.5	2.0	53.5	0.97	2.3	6.7174	1.8455	4.8719
Apr	27.7	1.7	55.5	102	3.8	6.6296	2.2720	4.3576
May	27	2.5	64.5	117.2	4.8	6.3207	2.5213	3.7994
Jun	24.8	3.6	76.5	84.6	6.2	5.5463	2.8445	2.7018
Jul	23.7	3.4	78.5	145.5	6.7	4.5014	3.0819	1.4195
Aug	23.4	3.4	78	157.6	6.6	4.4572	3.0850	1.3722
Sep	23.9	2.3	80	185.4	6.2	4.8533	2.9385	1.9148
Oct	23.5	2.0	78	201.2	6.1	5.1906	2.5170	2.6736
Nov	22.5	2.1	79	35.7	5.4	4.7661	2.2787	2.4875
Dec	21.1	2.5	73	9.6	3.7	4.5409	2.1480	2.3929

[a]Unit for cloud cover is Okta (0, clear sky; 8, fully cloudy sky)

$$AF = \frac{d_{available}}{d_{total}} \quad \ldots(9)$$

This record of minimum energy availability is being noted since August 1999 till present day on a daily basis.

Collector Performance

As an approximation, annual energy output of a SWH is given by

$$E_O = E_I \left[A_0 AF \right] \quad \ldots(10)$$

This works out to ~ 64% or 1269 kWh/m^2. This is independent of the number of extractions per day. This formula is justified from the approximation that drop in efficiency due to rise in water temp. is offset by energy absorbed by water due to diffuse radiation during cloudy

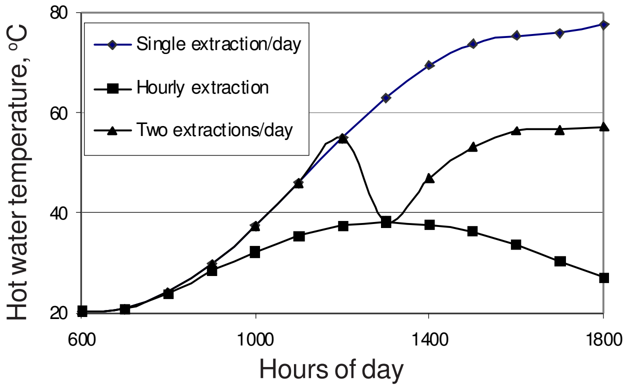

Fig. 1—Variation of annual average hot water temperature with hours of day

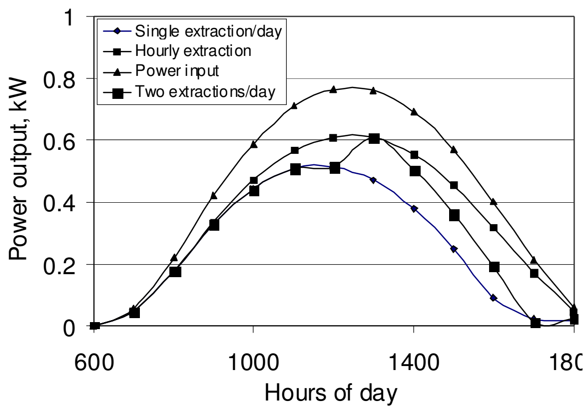

Fig. 2—Variation of annual average power input and output with hours of day

periods. Performance of SWHs is simulated for following boundary conditions (Fig.1):

A) Hourly Extraction and Charging Mode

Cold water is charged in from 06:00 h to 18:00 h at hourly intervals and hot water is extracted correspondingly. Extraction is at the end of 1 h interval (6:59 h to 18:59 h). Overnight extraction is at the start of hour interval (6:00 h).

B) Extraction and Charging Only Twice Daily

Cold water is charged in at 06:00 h and hot water is extracted at 12:00 h. Cold water is immediately recharged and hot water is extracted at 18:00 h. As another option, hot water is once extracted at 12:00 h (same day) and next morning at 06:00 h by storing it overnight during 18:00 h-06:00 h. Overnight extraction is at the start of hour interval (6:00 h).

C) Extraction and Charging Only Once Daily

Cold water is charged in at 06:00 h. Water is heated all through the day and extracted at 18:00 h. As another option, hot water is extracted next morning at 06:00 h by storing it overnight during 18:00 h and 06:00 h. The extraction is at the end of hour interval (18:59 h). Overnight extraction is at the start of hour interval (6:00 h).

Above conditions give terminal points of collector performance. Overnight storage simulates locally prevailing condition wherein hot water is utilized for bathing in early mornings. Electric back up reported[14,15] is only 15 % for 3 extractions per day, 24% for evening extraction and 39% for extraction next morning after overnight storage. High quality collectors (A_1, <4 W/m^2 ºC) are virtually unaffected by overnight drop. In absence of digital control, electric back up is not optimized.

Annual thermal energy output (for 2 m^2 collector system) is 1181.65, 1354.69 and 1585.89 kWh/m^2 at annual collector-tank system efficiency of 59.61, 68.34 and 80.0% for C, B, A respectively. When overnight storage of last extraction is considered (instead of 18:00 h, hot water is extracted at 06:00 h next day), corresponding annual energy output is 974.56, 1223.67 and 1490.80 kWh/m^2 at annual collector-tank system efficiency of 49.16, 61.73 and 75.20% for C, B, A respectively. In the case of single extraction, saturation in energy addition is observed after 15:00 h. In two extraction mode, annual energy output is 12.7% higher than that of one extraction mode. In hourly extraction mode, energy output is 25.5% higher than that of one extraction mode. If overnight storage is considered, then annual energy output will be 20.3% and 34.6% higher respectively for two cases (Fig. 2). Maximum temperatures reached at 18:00 h are 92.3° and 67.1ºC for one and two extraction modes. For hourly extraction mode, maximum temp. of 44.3ºC reached at 1300 h. Annual mean of maximum temp. reached at 18:00 h are 78ºC for one extraction and 57ºC for two extraction modes. For hourly extraction mode, mean of maximum temp. is 38 ºC reached at 13:00 h. Energy requirement not met by solar energy during June-Dec. is in range of 246-263 kWh/y (av 255.4 kWh/y). This corresponds to 20% of annual energy of 1277.5 kWh/d (Fig. 3). There is load mismatch in two ways – on sunny days energy extraction is saturated due to high water temp. in the tank and during cloudy days energy generation needs to be augmented.

Performance Enhancement

Performance can be enhanced in three ways by overcoming following limitations: i) Loss in energy output

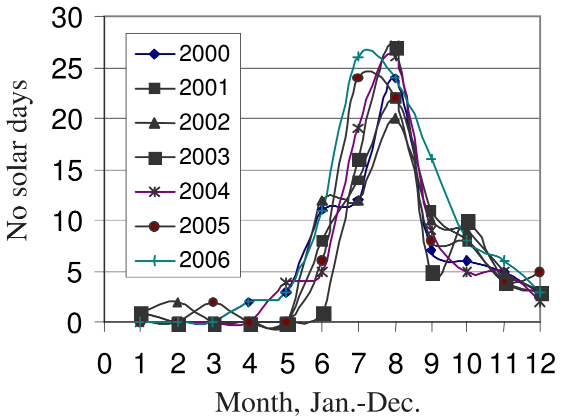

Fig. 3—Frequency of days in month when electric heater is used

due to saturation in hot water temp.; ii) Loss in energy output due to hot water temp. higher than task temp. (bathing, 38-42ºC) necessitating attemperation; and iii) Thermal loss in tank due to energization of electric heaters much before hot water is actually extracted.

Performance Optimizer

Performance optimizer is used to manage thermal energy generated by SWH and minimizes use of electric booster (back up) heater. It is a microcontroller based system, which assesses amount of thermal energy in tank at the end of day and estimates requirement of electrical energy; period of use of electrical heaters and time at which it is to be cut-in and cut-out. It then switches on and off electric heaters so as to meet output in time eliminating the need for electric heaters to be put on several hours earlier, thereby reduces thermal losses in tank for 4-6 h).

Second Tank with Digital Control

Dual tank systems have shown to give an edge of 10.8 % in annual energy output over single tank systems[16,17]. In present study, single tank is replaced by a two tank system with a software driven logic based control for switching over of connection to the collector from main tank (MT) to auxiliary tank (AT) and vice versa. Tank M consists of main tank (say 200 l) while Tank A consists of an auxiliary tank (say 100 l). The mutually exclusive connection of any tank to the collector can be switched over by a solenoid valve (thermal diode) based on setting water temp. for switchover from MT to AT tank. Energy efficiency of collector can be enhanced in three ways: i) On cloudy days, AT is connected to collector (MT is not connected) to raise water temp. higher because of smaller volume of water in AT and invoking of electric heaters is minimized; ii) On sunny days, MT is connected to the collector [When a pre-set water temp. is reached in MT (14:00 h) it then switches over to AT, thereby heating water in AT during remaining sunshine hours (14:00 h to 18:00 h). By this process in the single extraction mode, energy output corresponding to two extraction modes can be achieved]; and iii) On normal days, change over between MT and AT can be set to bathing temp. plus temp. drop during storage period between 18:00 h and the time of use.

Flow Rate of Air in Collector Zone and Water

Effect of flow rate of air in collector zone between flat plate and glass cover and water through collector tubes has been explored as an avenue for performance enhancement[18]. Active circulation in both these circuits can be accomplished by fans and pumps energized by small photovoltaic panels fixed on to collector longitudinal side. Winn & Winn[18] have shown that when A_1 is below 3.7 W/m^2 ºC and during periods of very low values of incident solar radiation, increasing flow rates will enhance performance. In other situations, there is no significant effect. Further, in naturally circulating thermosyphon systems, there are technical difficulties in fixing a pump in the line as it can hinder natural circulation. Hence, this option of flow control is not considered. Flow control could be a performance enhancement route for forced circulation collectors. Other performance enhancement routes involving convection suppression, two working fluids with multiple switchable tank circuits and two phase thermosyphon, are not practically successful. A novel neural network based diagnostic system is showing promise[19].

Conclusions

Performance analysis of thermosyphon SWHs with storage indicates that there is a thermal load mismatch. On sunny days, energy extraction is saturated due to high water temperature in tank and during cloudy days energy generation needs to be augmented. In case of single extraction, saturation in energy addition is observed after 15:00 h. In two extraction mode, annual energy output is 12.7% higher than that of one extraction mode. In hourly extraction mode, energy output is higher (25.5%) than that of one extraction mode. If overnight storage is considered then annual energy output will be 20.3% and 34.6% higher respectively for the two cases. Energy efficiency is enhanced in two (19%) and multiple extraction (36%) at the cost of lower water temp., which results in better source-task matching in case of usage for bath water. Performance of single extraction mode can be enhanced (20-30%) through dual tank system, wherein flow is switched onto second tank, when first tank temp. reaches its upper limit. Electrical back up during low solar insolation can be minimized using programmable controllers (performance optimizer), which selects the period of switching as well as the real time.

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