Performance Characteristics of Parabolic Trough Solar Collector System for Hot Water Generation

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ABSTRACT

A parabolic trough solar collector of aperture area one square meter was designed and developed for hot water generation. The collector's performance was tested according to ASHRAE Standard 93, 1986. The test slope and intercept of the collector efficiency equation were found to be 0.3865 and 0.6905 respectively. The collector efficiency equation obtained in the present work compares well with the other reported literature. The collector's time constant obtained from the test was 67 seconds. The collector's half acceptance angle determined from the test was 0.5°, which in combination with the tracking system maximum error (0.18°) implies that the collector works continuously at maximum possible efficiency.

Keywords - parabolic trough collector, collector test, collector thermal efficiency, collector time constant, acceptance angle, solar hot water generation.

1. INTRODUCTION

The parabolic trough collector (PTC) is currently receiving considerable attention, despite the fact that this solar concentrating device requires some level of solar tracking. The disadvantage inherent with this tracking requirement is apparently offset by the advantage associated with the high order of concentration available with this collector. Parabolic Trough Collectors (PTC) are generally employed for a variety of applications such as industrial steam generation [1] and hot water production [2]. Parabolic trough collectors are preferred for solar steam generation because temperatures of about 300 °C can be obtained without much degradation in the collector efficiency. Solar thermal power plants based on PTC are presently the most successful solar technology for electricity generation, as demonstrated by the Solar Electric Generation Systems (SEGS) plant at Kramer Junction in California. A feasibility study for the use of PTC in a hotel for hot water production was reported by Kalogirou and Lloyd [2] and it was shown that PTC could be more cost effective than the conventional flat plate collectors for large scale water production. The present work focuses on performance study of a new PTC of 1 m^2 aperture area, designed and developed to produce hot water.

2. DESIGN OF PARABOLIC TROUGH COLLECTOR

The design of a parabolic trough collector with 90° rim angle, employed in the present research work, is accomplished by considering the optimized collector aperture width and the receiver tube diameter. The simulation program written in MATLAB is used to predict the performance of the parabolic trough collector hot water generation system. Detailed design and simulation analysis of performance of PTC system is presented in Ref. [3].

The value of intercept factor, the most complex parameter involved in determining the optical efficiency of a PTC, depends on the size of the receiver, the surface angle errors of the parabolic mirror and solar beam spread. According to Guven and Bannerot [4], these errors or imperfections are of two types, namely random and non-random. Random errors are modeled statistically, by total reflected-energy distribution standard deviations σ at normal incidence,

(1)

Non random errors are determined by the misalignment angle error β (i.e. the angle between the reflected ray from the center of the Sun and the normal to the reflector's aperture plane) and the displacement of the receiver from the focus of the parabola i.e. receiver dislocation distance, .

For the evaluation of the intercept factor γ a closed-form expression developed by Guven and Bannerot [5] is used,

$$\gamma = \frac{1+\cos\phi_r}{2\sin\phi_r}\int_0^{\phi_r} Erf\left(\frac{\sin\phi_r(1+\cos\phi)(1-2d^*\sin\phi)-(\pi\beta^*(1+\cos\phi_r))}{\sqrt{2}\pi\sigma^*(1+\cos\phi_r)}\right) - Erf\left(-\frac{\sin\phi_r(1+\cos\phi)(1+2d^*\sin\phi)+(\pi\beta^*(1+\cos\phi_r))}{\sqrt{2}\pi\sigma^*(1+\cos\phi_r)}\right)\frac{d\phi}{(1+\cos\phi)} \qquad (2)$$

The collector rim angle ( ) is defined as the angle subtended by the edges of the reflector at the focus. A simple MATLAB program, which numerically evaluates the above expression is presented in Ref. [3].

The parabola trough of the PTC was accurately constructed of fiberglass. According to Guven and Bannerot [4], for carefully constructed collectors, the standard deviation of the distribution of local slope errors at normal incidence, σ_{slope} = 0.004 rad and the standard deviation of the variation in diffusivity of the reflective material at normal incidence, σ_{mirror} = 0.002 rad. The standard distribution of the Sun's intensity distribution σ_{sun} can be taken as 0.0025 rad. Therefore, from equation (1), σ = 0.0086 rad. The misalignment angle error β = 0.18^o (i.e. the maximum tracking error) and the displacement of the receiver from the focus of the parabola, is assumed as 2 mm. Using these inputs to the program, together with receiver diameter, the intercept factor is evaluated as 0.9563. Using a solar reflector material of reflectance (ρ_m) 0.974 (SOLARFLEX foil, Clear Dome Solar) [6], a special black painted copper tube receiver absorptance (α_r) of 0.9 and a low-iron glass cover transmittance (τ_e) of 0.9, a maximum optical efficiency (η_o) of 0.759 is obtained from the following expression.

γ is intercept factor, defined as the ratio of the energy intercepted by the receiver to the energy

(3)

reflected by the focusing device, A_f is geometric factor and θ is angle of incidence

3. DESCRIPTION OF PTC SYSTEM

In the present work, the PTC system used for hot water generation, which has been developed for experimentation, is presented in figure 1. The PTC system for hot water generation includes a PTC, a hot water storage tank (HWST) of well-mixed type and a circulating pump. The parabola of the present collector with a rim angle of 90^o is very accurately constructed of fibreglass. A flexible solar reflector material (SOLARFLEX foil) from Clear Dome Solar, San Diego with a reflectance of 0.974 is used in the present work. The solar receiver consists of a copper tube, a glass envelope and rubber cork seals at both ends of the glass envelope. The copper tube is coated with a heat resistant black paint and is surrounded by a concentric glass cover with an annular gap of 5 mm. The rubber corks are incorporated to achieve an air-tight enclosure. Water from the storage tank is pumped through copper tube, where it is heated and then flows back into the storage tank. The PTC rotates around the horizontal north/south axis to track the Sun as it moves through the sky during the day. The axis of rotation is located at the focal axis. The tracking mechanism consists of a low speed 12 Vdc motor and an embedded electronic controlled tracking system. The input signals to the control system are obtained from light dependent resistors. The pump for maintaining the forced circulation is operated by an on-off controller (Differential Thermostat), which senses the difference between the temperature of the water at the outlet of the collector (T_{fo}) and the storage tank water (T_l). The pump is switched on whenever this difference exceeds a certain value and off when it falls below a certain value. In the present work, the differential temperature controller value $(T_{fo} - T_l)$ is set as +2°C. The specifications of the PTC system are detailed in table 1.

4. PARABOLIC TROUGH COLLECTOR PERFORMANCE TEST

In the present work, the thermal performance of the parabolic trough solar collector was determined according to ASHRAE standard 93 to 1986 [7]. The thermal performance of the solar collector was determined by obtaining values of instantaneous efficiency for different combinations of incident radiation, ambient temperature and inlet water temperature. All parameters were measured under steady state or quasi-steady state conditions. The collector water outlet temperature (T_{fo}), ambient temperature (T_a) and storage tank water temperature (T_l) were recorded with the help of PT 100 - resistance temperature device (RTD) sensors. The solar beam radiation intensity was measured by a pyrheliometer and the mass flow rate of water by a rotameter. The wind speed was measured by a vane type anemometer.

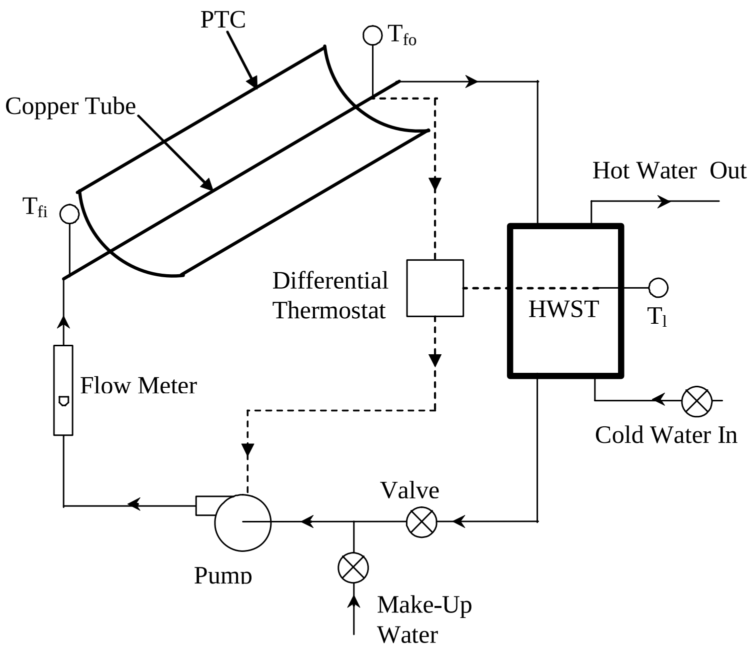

Fig. 1. Parabolic trough collector system.

Table 1. Parabolic trough Collector System Specifications

Items	**Value**
Collector Aperture	0.8 m
Collector Length	1.25 m
Rim Angle	90^o
Focal Distance	0.2 m
Receiver Diameter	12.8 mm
Glass Envelope Diameter	22.6 mm
Concentration Ratio	19.89
Water Flow Rate	0.7-1.0 lpm
Storage Tank Capacity	35 liters
Tank Material	Stainless Steel
Tank Insulation Material	Glass Wool
Insulation Thickness	50 mm
Water Pump	0.5 hp

4.1 Collector Thermal Efficiency Test

The thermal efficiency of a concentrating collector operating under steady state conditions can be described by ASHRAE 1986 [7],

(4)

The thermal efficiency from equation (4) is plotted against $\left(T_{fi} - T_a\right)/I$, a straight line will result provided is constant. The intercept is $F_R \eta_o$ and the slope is .

The performance curve of the PTC, as derived from a series of tests, carried out according to ASHRAE standard 93 (1986) on seven days, is shown in figure 2. An equation for the curve, established with 28 data points, is obtained using the standard technique of a least squares fit. The intercept is equal to 0.6905 and the slope is 0.3865. Therefore, the collector thermal efficiency equation for this PTC can be written as,

$$\eta = 0.6905 - 0.3865\left(\frac{T_{fi} - T_a}{I}\right) \tag{5}$$

Using a calculated value of F_R = 0.995 and a concentration ratio C = 19.89,
we obtain, Optical efficiency, η_o = 0.6940 and
Heat loss coefficient, = 7.73 W/m^{2}K

Theoretical calculation of the intercept and slope together with the experimental values are presented in table 2. The theoretical values are estimated by means of a MATLAB computer program [3]. It can be observed from table 2 that there is a minor difference between the theoretical and the experimental results with respect to test slope (5.92 %) and a moderate difference is shown for the test intercept (9.37 %), which demonstrates that the design procedure followed in the present work is correct.

The collector efficiency equation compares well with those for other reported research works as presented in table 3.

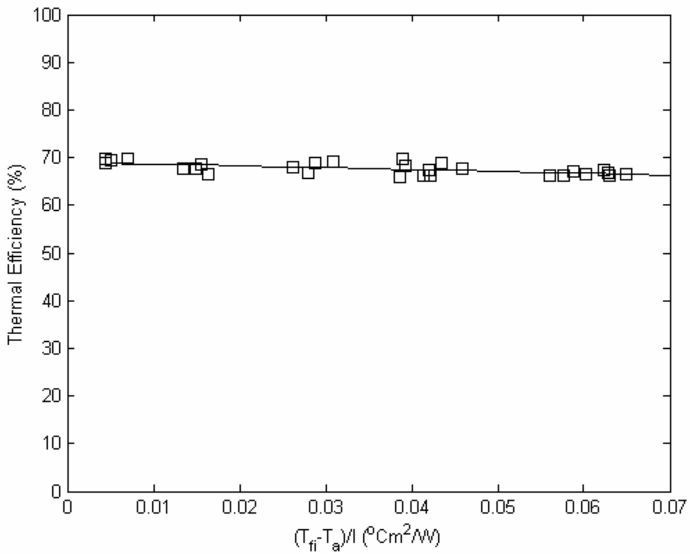

Fig. 2. Collector thermal efficiency curve.

Table 2. Collector Performance

S. No.	Item	Test Intercept	Test Slope
1	Theoretical Performance [3]	0.7552	0.3636
2	Experimental Performance [Present Work]	0.6905	0.3865
3	% Difference	9.37	5.92

Table 3. Comparison of Collector Efficiency Equations

Efficiency equation	Reference
$\eta = 0.66 - 0.233\left(\frac{\Delta T}{I}\right)$	Ref. 8
$\eta = 0.65 - 0.382\left(\frac{\Delta T}{I}\right)$	Ref. 9
$\eta = 0.642 - 0.441\left(\frac{\Delta T}{I}\right)$	Ref. 10
$\eta = 0.638 - 0.387\left(\frac{\Delta T}{I}\right)$	Ref. 11
$\eta = 0.6905 - 0.3865\left(\frac{\Delta T}{I}\right)$	This Paper [Present Work]

4.2 Collector Time Constant Test

The time constant of a collector is the time required for the fluid leaving the collector to reach 0.632 of its ultimate steady state value after a step change in incident radiation. i.e. the time constant of collector is the time required for the quantity $\left(T_{fo,f} - T_{fo}(\tau)\right) / \left(T_{fo,f} - T_{fi}\right)$ to change from 1.0 to 0.368 [7]. where $T_{fo}(\tau)$ is the outlet temperature of collector fluid after time (τ) and is the final outlet temperature of collector fluid.

The time response of the parabolic trough solar collector has to be determined in order to evaluate the transient behaviour of the collector, and to select the proper time intervals for the steady state or quasi-steady state efficiency tests. Whenever transient conditions exist, the equality defined by equation (4) does not govern the thermal performance of the collector, since part of the solar energy absorbed is used for heating up the collector and its components or part of the energy lost results in cooling the collector.

The time constant for a solar collector was determined as follows:

The collector was initially at the defocused position. The collector was suddenly moved to the focused position and measurements were continued for every 10 seconds until steady state conditions had been achieved (figure 3). During the test the collector water inlet temperature was maintained at the ambient temperature. The time constant of the collector was evaluated as 67s.

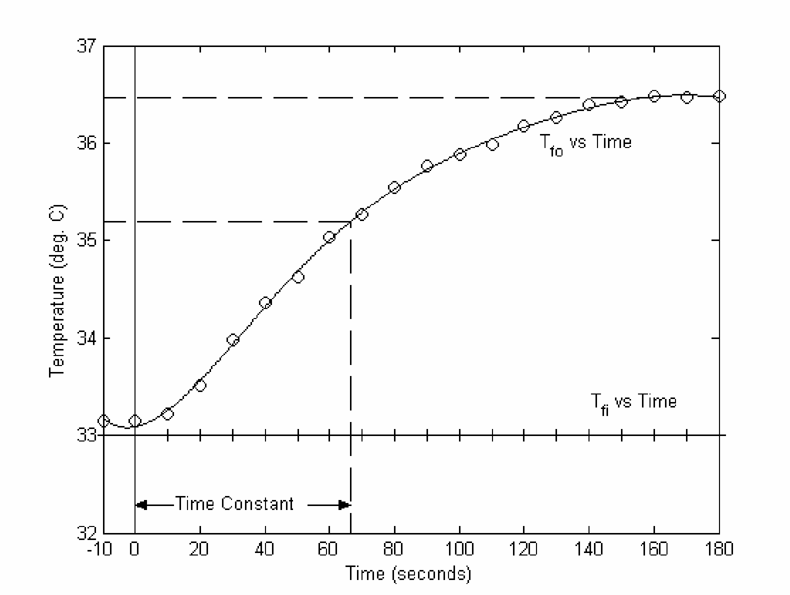

Fig. 3. Collector time constant.

4.3 Collector Acceptance Angle Test

An embedded electronic controlled tracking system has been connected to a parabolic trough collector with aperture width 0.8 m, length 1.25 m, rim angle 90^{o} and receiver diameter 12.8 mm. Since collector acceptance angle characterises the effect of errors in the angular orientation of the tracking mechanism, a test to determine the collector acceptance angle was carried out according to ASHRAE standard 93 to 1986 [7]. With the tracking mechanism disengaged, the collector efficiency was determined at various out of focus angles as the Sun traveled over the collector's plane. The thermal efficiency of the collector operating under steady state conditions is given by [12],[13].

Thermal efficiency, $$\eta = \frac{\dot{m} c_p (T_{fo} - T_{fi})}{A \times I} \quad (6)$$

The inlet temperature of water, T_{fi} was equal to the ambient temperature, (T_a = 306 K) and water was circulated at the specified flow rate i.e. 0.7 kg/min. During the test, the direct beam of solar irradiation on the plane of the collector aperture was between 800 and 810 W/m^2. The outlet temperature of water, T_{fo} was continuously monitored for every second over a 30 minutes period. The efficiency factor is computed as the ratio of thermal efficiency at a particular out of focus angle to the maximum thermal efficiency at normal incidence.

The angle of incidence measured from the normal to the tracking axis is plotted against the efficiency factor (Figure 4). The collector acceptance angle is defined as the range of incidence angles measured from the normal to the tracking axis in which the efficiency factor varies by not more than 2% from the normal incidence angle [7]. Therefore, from figure 4, the acceptance angle of the collector is approximately 1^o. The tracking system accuracy, i.e. the out of focus angle required to initialise the system, can be determined by measuring the period between successive operation of the motor [14]. The tracking system accuracy depends on the Sun's intensity level. The accuracy of the embedded electronic controlled tracking mechanism developed for the present PTC system is 0.1^o with radiation level of 700 W/m^2 and 0.18^o with radiation level of 200 W/m^2. Thus the tracking mechanism maximum error is 0.18^o, which is much greater than the required 0.5^o (collector half acceptance angle value) determined from the collector acceptance angle test.

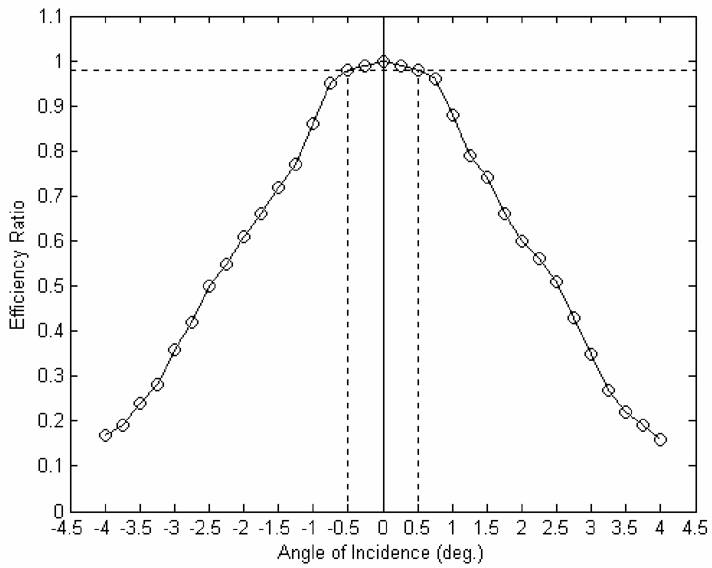

Fig. 4. Collector acceptance angle.

5. CONCLUSION

The performance tests of the new parabolic trough collector designed and developed for hot water generation have been carried out according to ASHRAE standard 93 to 1986. In the present work, the experimentally calculated values of test slope and test intercept are 0.3865 and 0.6905 respectively. The collector efficiency equation compares well with the other reported research works. The test slope and test intercept values vary only by 5.92 % and 9.37 % respectively from the theoretically calculated values, which demonstrates that the design procedure followed in the present work is correct. The time constant for the new PTC is determined as 67 seconds, which suggests that the collector has fast response to maintain quasi-steady state conditions. The embedded electronic controlled tracking mechanism has proved to be accurate for the present solar energy application from the collector acceptance angle test that was carried out according to ASHRAE standard 93 to 1986. The tracking mechanism maximum error is determined to be 0.18^o only. The accuracy of the new tracking mechanism is much greater than the required 0.5^o, which is determined from the collector acceptance angle test. This implies that the collector works continuously at maximum possible efficiency at all times.

6. NOMENCLATURE

A	Collector aperture area (m^2)
A_f	Geometric factor (m^2)
C	Concentration ratio
c_p	Collector fluid specific heat capacity (J/kg-K)
$D_{r,o}$	Receiver tube outer diameter (m)
dr	Receiver dislocation distance (mm)
d^*	Universal nonrandom error parameter due to receiver dislocation and reflector profile errors [$d^* = dr/D_{r,o}$]
F_R	Heat removal factor
I	Beam or direct radiation (W/m^2)
L	Receiver tube length (m)
$\dot{m}$	Mass flow rate (kg/s)
T_a	Ambient temperature (K)
T_{fi}	Collector water inlet temperature (K)
T_{fo}	Collector water outlet temperature (K)
T_l	Storage tank water temperature (K)
U_L	Overall heat loss coefficient (W/m^2-K)
W_a	Aperture width (m)
α_r	Receiver absorptivity
β	Misalignment angle error (degree)
β^*	Universal nonrandom error parameter due to angular errors [$\beta^* = \beta C$]
ϕ_r	Collector rim angle (degree)
γ	Intercept factor
η	Thermal efficiency (%)
η_o	Optical efficiency (%)
θ	Angle of incidence (degree)
σ	Total reflected-energy standard deviations at normal incidence
σ^*	Universal random error parameter [$\sigma^* = \sigma C$]
σ_{sun}	Standard deviation of the energy distribution of the sun's rays at normal incidence

σ_{slope} Standard deviation of the distribution of local slope errors at normal incidence

σ_{mirror} Standard deviation of the variation in diffusivity of the reflective material at normal incidence

τ_e Transmittance of envelop material

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