THEORETICAL ANALYSIS AND EXPERIMENTAL VERIFICATION OF PARABOLIC TROUGH SOLAR COLLECTOR WITH HOT WATER GENERATION SYSTEM

by

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The modeling of a parabolic trough collector with hot water generation system with a well-mixed type storage tank using a computer simulation program is presented in this paper. This is followed by an experimental verification of the model and an analysis of the experimental results. The maximum difference between the predicted and the actual storage tank water temperature values is found as 9.59% only. This variation is due to the difference between the actual weather during the test period compared to hourly values and the convection losses from the collector receiver, which were not constant as accounted by the computer simulation program.

Key words: *parabolic trough collector, storage tank, hot water generation, system performance, simulation program*

Introduction

India is generally endowed with renewable energy resources: solar, wind, and biomass. India receives solar energy equivalent to over 5000 trillion kWh/year, which is far more than the total energy consumption of the country. The daily average global radiation is around 5 kWh per sq. m. per day with the sunshine hours ranging between 2300 and 3200 per year [1]. India today has among the world's largest programs in solar energy. The Indian Ministry of non-conventional energy sources is implementing country-wide programs on: (1) Solar Thermal Program and (2) Solar Photovoltaics Program. Solar thermal technologies utilize the heat energy from the sun for various purposes. Depending on the technology, the temperature of the output thermal energy can vary from as low as ambient temperature to as high as 3000 °C. This opens up a vast area of applications including power generation and refrigeration. Solar water heating is an important application of solar energy. From many types of solar collectors developed, three types merit further consideration for hot water generation: the flat plate collector (FPC) [2], the compound parabolic collector (CPC) [3], and the parabolic trough collector (PTC) [4]. The first two are stationary collectors, whereas the last one is a tacking collector. PTCs are generally of medium concentration ratio (15-40) and hence they require some level of solar tracking. The advantage of concentrating collectors is that the heat losses are inversely proportional to the concentration ratio. The most important advantage of PTC as compared with the other two types of collectors is its ability to function at high temperatures with high efficiency. For example, at a temperature of 100 °C, PTCs works at an efficiency of about 62%, CPCs at about 32% and the FPC at about 10% [5]. In recent days, PTC has been used many applications such as steam generation for industrial applications [6] and power generation [7, 8], hot water generation, sea water desalination [9, 10], solar photocatalysis [11], solar detoxification of organic pollutants [12], *etc*. The objective of the modeling presented in this paper is to investigate the performance of a PTC hot water generation system and compare the results with the actual system performance.

Modeling of the PTC hot water system

In the present work, a new parabolic trough collector system, which has been developed for hot water generation, is presented in fig. 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° is very accurately constructed of fiber glass. A flexible solar reflector material (SOLARFLEX foil) from Clear Dome Solar, San Diego, Cal., USA [13] 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 0.5 cm. The rubber corks are incorporated to achieve an air-tight enclosure. Water from

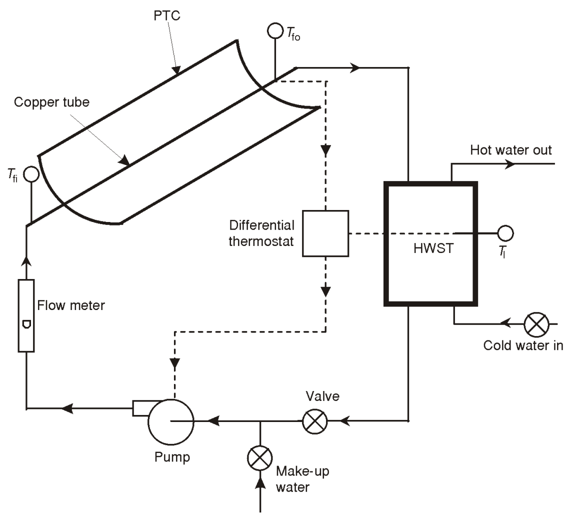

Figure 1. Parabolic trough collector with storage tank

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 V D. C. motor and an embedded electronic control 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. It is assumed that the water in the storage tank is always well mixed and consequently is at a uniform temperature, T_l, which varies only with time. The specifications of the PTC system are detailed in tab. 1.

Table 1. Parabolic trough collector system specifications

Items	Value
Collector aperture	0.8 m
Collector length	1.25 m
Rim angle	90°
Focal distance	0.2 m
Receiver diameter	12.8 mm
Glass envelope diameter	22.6 mm
Concentration ratio	19.89
Water flow rate	1.0 l/min.
Storage tank capacity	35 liters
Tank material	Stainless steel
Tank insulation material	Glass wool
Insulation thickness	5 cm
Water pump	367.65 W

Simulation program

In the present work, a simulation model based on MATLAB program is developed to determine the optical and thermal characteristics of a parabolic trough collector and the hourly storage tank water temperature. Detailed analysis of the collector performance based on the collector performance simulation program is presented in the paper [14]. The program gets the required input such as system specifications given in tab. 1, hourly solar beam radiation, ambient temperature, and initial storage tank temperature and determines the thermal and optical characteristics of the PTC. Finally, the last output from the program is that the new storage tank water temperature after every one hour time interval is determined. This new storage tank temperature is taken as storage tank liquid initial temperature, T_{li} at the next hour. Thus the program computes the hourly storage tank water temperature. It is assumed that no hot water is used. The program flow chart is shown in fig. 2.

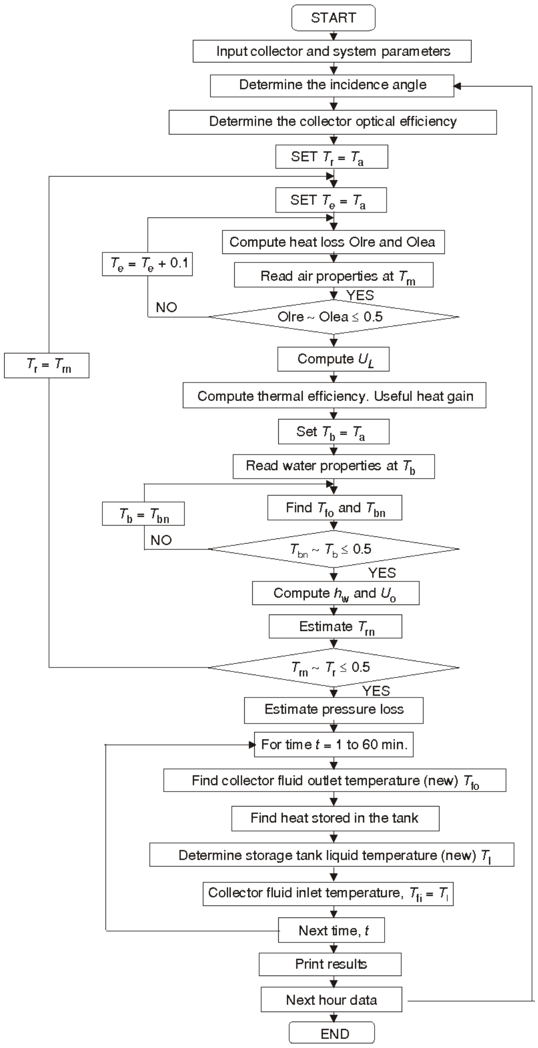

Figure 2. Simulation program flow chart

Experimentation

The experimental set up used in the present work for assessing the accuracy with which the simulation program predicts the PTC hot water generation system performance is as shown in fig. 1. The thermal performance of the parabolic trough solar collector according to ASHRAE standard 93, 1986 [15] and the hourly storage tank water temperature were determined. The PTC hot water system performance is determined for different combinations of incident radiation, ambient temperature and inlet water temperature. The solar beam radiation intensity (I) 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. 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. All parameters were measured under steady-state or quasi--steady-state conditions as a function of time *i. e*. for every 15 minutes period from 10.00 am to 16.00 pm over six months from March to August.

The thermal efficiency of a concentrating collector operating under steady state conditions can be described by ASHRAE 1986 [15]:

$$\eta \quad F_R \eta_o \quad \frac{F_R U_L}{C} \frac{T_{fi} \quad T_a}{I} \tag{1}$$

The thermal efficiency from eq. (1) is plotted against $(T_{fi} - T_a)/I$, a straight line will result provided U_L is constant. The intercept is $F_R \eta_o$ and the slope is $F_R U_L/C$.

Theoretical calculation of the intercept and slope using the simulation program [14] together with the experimental values are presented in tab. 2. It can be observed from tab. 2 that there is a minor difference between the theoretical and the experimental results with respect to the test slope (5.92%) and a moderate difference is shown for the test intercept (9.37%)

Table 2. Collector performance

No.	Item	Test intercept	Test slope
1	Theoretical performance	0.7552	0.3636
2	Experimental performance (present work)	0.6905	0.3865
3	Difference [%]	9.37	5.92

For the estimation of hourly storage tank water temperature, the following equation is used [16]:

$$T_{l\,new} \quad T_{l\,old} \quad \frac{Q_u \quad Q_l \quad (UA)_t (T_{l\,old} \quad T_a)}{(\rho V c_p)_l \quad (\rho V c_p)_t} \tag{2}$$

where $(UA)_t$ the product of the overall heat transfer coefficient between the tank water and the ambient air and surface area of the tank [W] and $(\rho V c_p)_l$ represents the heat capacity of the water in the tank [J], the heat capacity of the tank material [J]. In the present work, Q_l is taken as zero and Δt =1 h.

The results from the experiments carried out with the newly developed PTC system are presented in tab. 3. As can be seen from this table, the difference between the predicted ($T_{l\,sim}$) and the actual storage tank temperature ($T_{l\,exp}$) for all the six months is reasonably small.

Table 3. Comparison of predicted and actual storage tank temperature

Day	Tank water	Temperature, [°C]					
		11.00 h	12.00 h	13.00 h	14.00 h	15.00 h	16.00 h
March 10, 2005	$T_{l\,sim}$	45.32	53.55	61.25	67.51	72.34	77.48
	$T_{l\,exp}$	43.65	53.28	60.41	65.83	70.34	74.66
	Difference [%]	*3.83*	*0.51*	*1.39*	*2.55*	*3.22*	*3.78*
April 17, 2005	$T_{l\,sim}$	50.41	58.50	65.93	72.52	77.90	83.52
	$T_{l\,exp}$	49.77	57.94	65.53	71.19	74.81	77.67
	Difference [%]	*1.28*	*0.97*	*0.61*	*1.87*	*4.13*	*7.53*
May 15, 2005	$T_{l\,sim}$	49.83	57.43	64.42	70.60	75.65	80.89
	$T_{l\,exp}$	47.65	55.84	62.24	67.61	72.35	76.31
	Difference [%]	*4.58*	*2.85*	*3.50*	*4.42*	*4.56*	*6.00*
June 13, 2005	$T_{l\,sim}$	46.26	54.51	62.33	68.69	74.44	79.43
	$T_{l\,exp}$	42.21	51.32	59.29	66.42	72.83	78.45
	Difference [%]	*9.59*	*6.21*	*5.13*	*3.42*	*2.21*	*1.25*
July 10, 2005	$T_{l\,sim}$	43.43	50.85	57.69	63.76	68.72	73.87
	$T_{l\,exp}$	41.06	49.87	57.01	62.51	67.02	70.68
	Difference [%]	*5.77*	*1.97*	*1.19*	*1.99*	*2.54*	*4.51*
August 16, 2005	$T_{l\,sim}$	47.01	56.34	64.81	69.72	74.01	79.53
	$T_{l\,exp}$	45.22	55.83	62.88	68.13	71.97	75.15
	Difference [%]	*3.96*	*0.91*	*3.07*	*2.33*	*2.83*	*5.83*

The difference between the theoretical and the experimental storage tank temperature values may be accounted for by the following reasons:

– the magnitude of solar beam radiation varies significantly and that of the ambient air temperature varies slightly with in one hour period. But those values are taken as constant during one hour in the simulation program, and

– the wind velocity, one of the important parameters, determines the convective losses is considered as constant (0.1 m/s) in the simulation program. But there was light wind velocity variation in all test conditions.

Conclusions

The modeling of a parabolic trough collector hot water generation system with a well-mixed type storage tank using a computer simulation program is presented in this paper. The simulation program predicts the newly developed PTC hot water system performance to an accuracy of 9.59% and therefore the model can be used for long term prediction of parabolic trough collector with hot water generation system performance.

Nomenclature

A – collector aperture area, [m^2]
C – concentration ratio, [–]
c_p – specific heat capacity of water, [$Jkg^{-1}K^{-1}$]
F_R – heat removal factor, [–]
I – beam or direct radiation, [Wm^{-2}]
Q_l – rate at which energy is being discharged to the load, [W]
Q_u – rate of useful heat received from the collector, [W]
T_a – ambient temperature, [K]
T_e – glass envelope surface temperature, [K]
T_{fi} – collector water inlet temperature, [K]
T_{fo} – collector water outlet temperature, [K]
T_l – storage tank water temperature, [K]
$T_{l\,i}$ – initial storage tank water temperature, [K]
$T_{l\,new}$ – new storage tank water temperature, [K]
$T_{l\,old}$ – old storage tank water temperature, [K]
T_r – receiver tube surface temperature, [K]
Δt – time interval, [h]
U_L – overall heat loss co-efficient, [$Wm^{-2}K^{-1}$]
V – volume, [m^3]

Greec letters

η – thermal efficiency of the collector, [%]
η_o – optical efficiency, [%]
ρ – density, [kgm^{-3}]

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