

# Experimental Study of Sunearth Flat Plate Solar Collector

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**Abstract-** In this paper, results are presented for the testing of a flat plate solar thermal collector. A wealth of technical data regarding the SUNEARTH vendor name brand of flat plate solar collectors is presented to provide references for Solar Engineers. The thermal performance curve is used to determine the air-collector heat removal factor of the device, which is then compared with the manufacturer's data. The diurnal system efficiency characteristics of this device are also presented herein. These results afford a pragmatic baseline for other researchers seeking to benchmark the performance of their solar collectors.

**Keywords-** Solar Thermal; Flat Plate Solar Collector; Energy Efficiency

## I. INTRODUCTION

Considering the energy crisis that we find ourselves in these days due to our heavy dependence on fossil fuels, finding alternate ways to provide necessary energy for our expanding society has become crucial to our future generations. With research and public awareness, harnessing solar radiation in locations such as Southern California is starting to be regarded as a reliable source of energy and is also becoming a well supported alternative to fossil fuels for our energy needs. In central Europe, approximately 90% of solar collectors are of the flat plate variety. Only with inspiring curiosity in and promoting education about solar energy, will the widespread implementation of this energy source become a reality. Made possible by the donation of the flat plate solar collector by SunEarth, Inc., this project has provided the foundation for a hands-on learning experience for many future mechanical engineering students through offering an interactive laboratory exercise which will require the basic engineering knowledge of fluid mechanics, heat transfer, mechanical measurements and solar thermal engineering. The current study is in family with prior researchers including the Alarez et al. (2010), Rodriguez-Hidalgo et al. (2011), Rojas et al. (2008) and Thirugnanasambandam et al. (2010). Comprehensive reviews on solar collectors are given by Kalogirou (2004) and Tian and Zhao (2013) while Andersen and Furbo (2009) provide theoretical correlations for solar collectors in the Netherlands. A flat plate collector (FPC) can operate with different heat transfer fluids (HTF) depending on the application and temperature ranges needed. A concentration of propylene glycol can be used when the environment is known to be colder and the solar collector does not have high exposure to the sun whereas in sunnier places, regular water may be used. Choosing the correct HTF is very important because its properties, such as its specific heat  $C_p$ , help determine the amount of energy that can be absorbed and transferred to the nearby storage tank in a set amount of time. This amount of useable energy  $Q_u$  is directly proportional to the difference in temperature and can therefore be calculated by recording the inlet temperature, outlet temperature, and mass flow rate of the HTF via the relationship

$$Q_u = mC_p(T_{fo} - T_{fi}) \quad (1)$$

where  $T_{fi}$  denotes the inlet temperature, and  $T_{fo}$  denotes the outlet temperature. The useable energy can also be used to find the efficiency of the FPC. There are various efficiencies that can be used to describe a solar collector's performance although some are more descriptive than others. The collector's instantaneous efficiency is inversely proportional to solar irradiation and collector aperture area and will therefore vary over the course of the day. This data would be insufficient in describing the collector and therefore data must be taken throughout the course of a given time in order to take the average efficiency. The following equation describes the relationship mentioned above between useful energy, solar insolation  $I_c$ , and aperture area  $A_c$ .

$$\eta_c = \frac{Q_u}{I_c A_c} \quad (2)$$

As the HTF flows through the manifold of the FPC, it absorbs energy through conduction and radiation due to the solar irradiation acting incident on the collectors' absorber plate. It then flows into a storage tank that will be used to heat up potable water. This is achieved by using a submerged heat exchanger (SHX) coil. The SHX is composed of 120 feet of copper tubing that is wrapped around the storage tank's interior wall. As the fluid enters the SHX, it transfers heat into the storage water as it

flows through the coil and exits at a lower temperature. The cooled water will recirculate through a closed loop and the cycle will repeat throughout the day. This process is shown in the Figure 1 below.

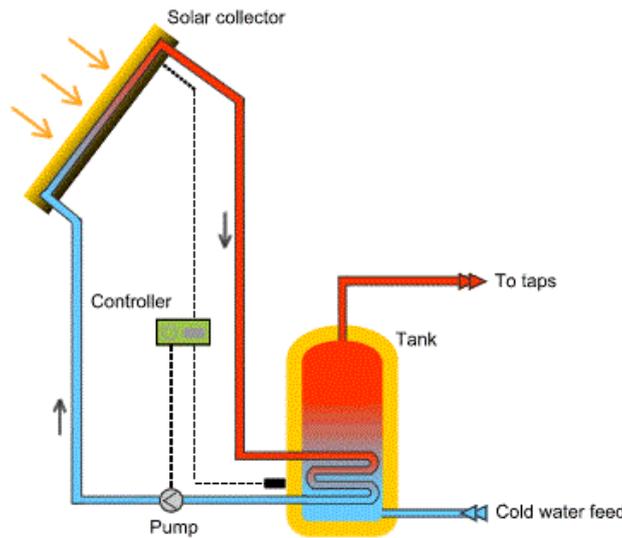


Fig. 1 Depiction of flow process in a closed-loop solar collector system

Note that the temperature in the storage tank will not be uniform due to the convective cell phenomena. Because of the placement of the SHX, the water will tend to heat up on the bottom of the storage tank first. Recall that as the temperature of water increases, its density will decrease. Therefore, the heated water will tend to flow upwards resulting in a temperature gradient within the storage tank thereby creating a convective cell. This phenomenon also occurs in the air space between the glass cover and absorber plate of the FPC itself, though the temperature gradients caused by it are negligible due to the dominating and highly non-linear nature of radiation acting incident on the absorber plate. In order to maximize the efficiency of the FPC, it must be oriented so that it receives the most sunlight possible, especially since FPCs are typically in a fixed position. Due to the Earth’s orbit around its own axis, which affects the sun’s angle with the Earth (also known as the declination angle), the ideal orientation will change according to the geographical location on the Earth. According to Stine and Geyer (1979), this ideal orientation is found to be the latitudinal angle in which it is placed.

II. EXPERIMENTAL SETUP

The testing configuration for a liquid-type solar collector is dictated by ASHRAE Std. 93-77, “Methods of Testing to Determine the Thermal Performance of Solar Collectors” ASHRAE 93-77 (1993). Figure 2 is the test set-up used by our research group at the Solar Thermal Alternative Renewable Energy Lab at California State Polytechnic University at Pomona’s Mechanical Engineering Department in close adherence to ASHRAE 93-77.

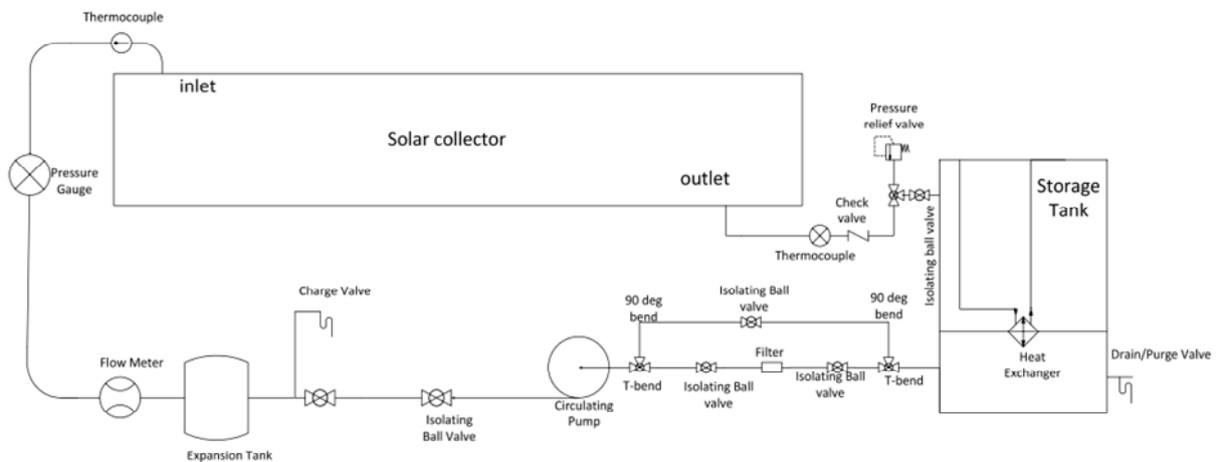


Fig. 2 Experimental test set-up per ASHRAE Standard 93-77.

Our test facility consists of the SUNEARTH Flat Plate Solar Collector, a 90 gallon water storage hot water tank, pump, and instrumentation. As shown in Figure 2, ASHRAE Standard 93-77 mandates the use of the various components such as the check valve, isolating valves, drain/purge valve, by-pass valve, etc. The actual system under test in this investigation is shown below in Figure 3.



Fig. 3 SUNEARTH Solar Thermal Collector device under test

The manufacturing and construction details for the SUNEARTH Solar Thermal Collector are shown in Figure 4. The technical specifications of the SUNEARTH collector tested in our study are included in the Appendix of this paper.

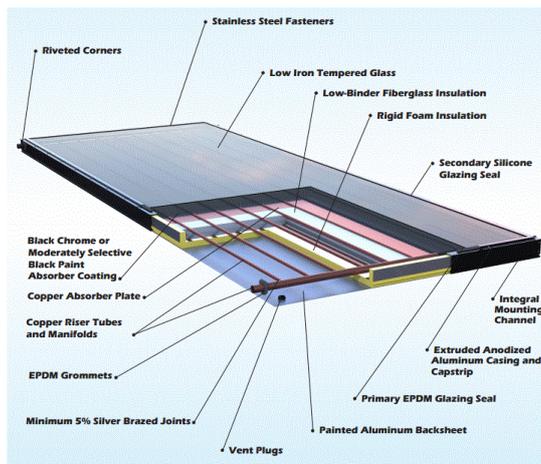


Fig. 4 SUNEARTH solar thermal collector construction details (SUNEARTH, Inc. (2013))

A. Instrumentation

The following instrumentation was used for this experiment: Type K Thermocouples, G ½ Flow Sensor, Arduino UNO Microprocessor Data Acquisition board, and a Daystar DS-05 Solar Meter. The flow sensor was connected to the Arduino UNO board as shown in Figure 5. The flow rate in GPM is given by  $f \cdot 0.264 / 7.5$ , where  $f$  is the Pulse Frequency. The mass flux flow rate of the SUNEARTH FPC had a nominal value of  $0.2 \text{ kg/s} \cdot \text{m}^2$  ( $14.7 \text{ lb/hr} \cdot \text{ft}^2$ ).

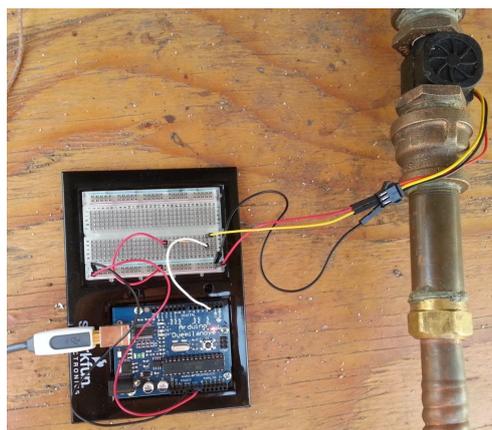


Fig. 5 Flow Sensor connected to Arduino Board

III. RESULTS AND DISCUSSION

Efficiency and solar irradiance diurnals are shown below in Figure 6. In Figure 6, averaged hourly efficiencies are plotted versus time showing the distribution throughout the day. The efficiency peaks at approximately 2:00 PM with a value of 88% when the solar intensity is  $650 \text{ W/m}^2$ . The solar irradiation diurnal peaks at 12:30 PM corresponding to a maximum solar irradiation value of  $800 \text{ W/m}^2$ .

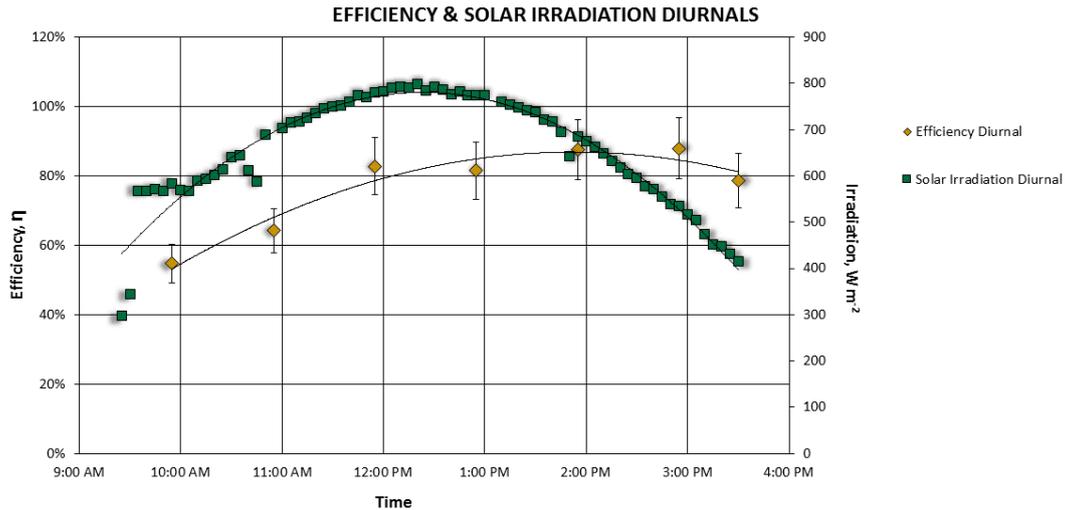


Fig. 6 Efficiency and solar irradiation diurnals

The data of Figure 6 compare well qualitatively to previous studies such as the work of Rodriguez-Hidalgo et al. (2011) and Zambolin and Del Col (2010). Figure 7 illustrates the Flat Plate Collector’s thermal performance.

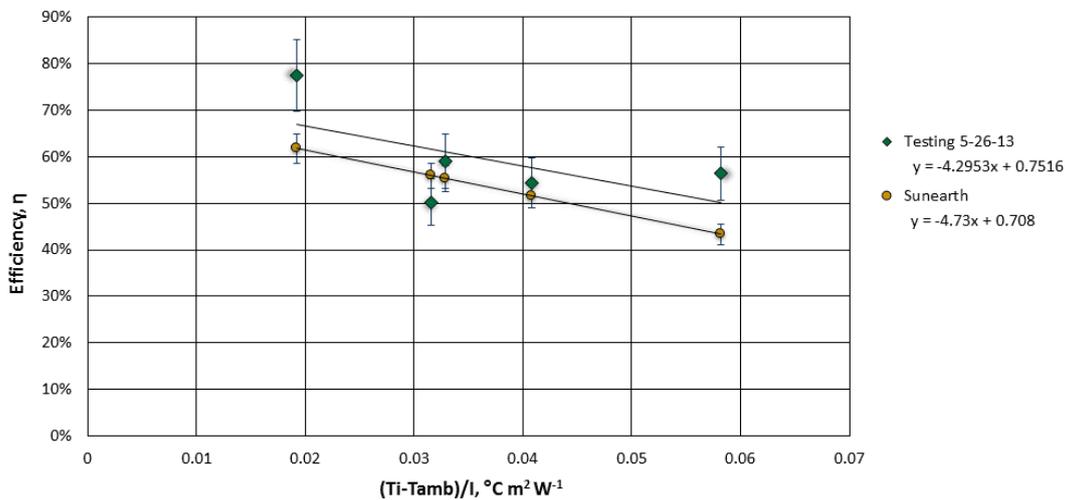


Fig. 7 Thermal solar collector performance curves

The results of Figure 7 are in qualitative agreement with similar flat plate solar collectors as found in the comprehensive review of Kalogirou (2004). The range of  $0 < (T_i - T_{amb})/I < 0.025$  is for pool heating applications, while the range of  $0.03 < (T_i - T_{amb})/I < 0.06$  is for double-glazed flat plate collectors, applicable to domestic hot water applications. In this range of  $0.03 < (T_i - T_{amb})/I < 0.06$ , Kalogirou (2004) reports a range of collector efficiencies from 80% (for  $(T_i - T_{amb})/I = 0.03$ ) to 45% (for  $(T_i - T_{amb})/I = 0.06$ ), which is in qualitative agreement with our present results. Additionally the data presented by Rojas et al. (2008) reports that in the range of  $0.02 < (T_i - T_{amb})/I < 0.06$ , the collector efficiency is approximately 55% (for  $(T_i - T_{amb})/I = 0.02$ ) to 30% (for  $(T_i - T_{amb})/I = 0.06$ ). From Figure 7, it is seen that our current data fall within the range of data reported by for Rojas et al. (2008) within 5%. Examination of the data in Figure 7 warrants an explanation of how the uncertainties of the measurements are determined. To this end, a Root-Sum-Squared technique was employed to assess both the bias and statistical error of the device under test. The Root-Sum-Squared model was of the form

$$u_x = \pm \sqrt{\sum_{j=1}^N e_j^2} = \pm \sqrt{B_x^2 + t_{CI,n-1} \frac{S_x}{\sqrt{n}}} \tag{3}$$

where  $u_x$  is the uncertainty in the measurement,  $n$  is the number of data points,  $e_j$  denotes the elemental error,  $B_x$  is the bias error, and the stochastic error is given by the product of the confidence interval involving the Student t-distribution,  $t_{CI,n-1} \frac{S_x}{\sqrt{n}}$ . The error bars of Figure 7 are set to a  $\pm 3S_x$  ( $\pm$ three-sigma) deviation. The data of Figure 7 is illustrative of similar test results as obtained by Rojas et al. (2008) and Goswami, Kreith and Krieder (2000). Continuing, from Figure 7, the

best fit line has a slope,  $|F_R U_c| = 4.2953 \text{ W/m}^2\text{-K}$ , while the Y-intercept results in the  $F_R \tau_s \alpha_s$  term which places a practical limit on the maximum efficiency. Recall, the term  $F_R$  is deemed as the collector heat removal factor,  $U_c$  is the collector's overall heat transfer loss coefficient, while  $\tau_s \alpha_s$  characterizes the solar thermal radiation optical performance of the glass comprising the covers of the the solar collector. The value for  $|F_R U_c| = 4.2953 \text{ W/m}^2\text{-K}$  is in agreement with suggested values found in Goswami, Kreith and Krieder (2000), wherein values of 3.2 to 4.8 are reported. From Figure 7, the Maximum System Efficiency is 75.16%. Again this value is in agreement with the range of values reported by Goswami, Kreith and Krieder (2000), whereby it is found that the efficiency is on the order of 74.5%. We compare this finding to the SUNEARTH, Inc. ISO Efficiency Equation given below

$$\eta = 0.750 - 3.0460 \left( \frac{P}{G} \right) - 0.01989 \left( \frac{P^2}{G} \right); P = (T_i - T_a) \quad (4)$$

In the above relationship,  $G$  denotes the gross area of the collector. Maximum system efficiency is 75.2%, and the percentage error when compared to SUNEARTH's data is only 6.16%. Thus, both slopes and y-intercepts are found to be within 10% of one other.

#### IV. CONCLUSIONS

The results of the performance testing and characterization of a solar flat plate collector have been presented herein. The data collected for the device under test is found to be in agreement with vendor specification sheets and theory within 10%. The data provided herein will be found to be of pragmatic value to the community of Solar Thermal Engineers seeking to perform characterization testing of flat plate solar thermal collectors. Future work will focus on quantification of the effects of forced convection on the performance of the solar collector.

#### ACKNOWLEDGMENT

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Dr. Anderson is a member of ASME, ASES and AIAA.

## APPENDIX

### A. Specifications

The following shall be the specifications for the solar collectors. Collectors shall be SunEarth Empire model UC-40, and shall be of the glazed liquid flat plate type. Collectors shall be tested in conformance with ASHRAE 93-2003 and Solar Rating and Certification Corporation (SRCC)100-05, and have their thermal performance rated according to SRCC Document RM-1. The collectors shall be certified by SRCC and the Florida Solar Energy Center (FSEC), and listed by the International Association of Plumbing and Mechanical Officials (IAPMO).

### B. Dimensions

Length 3.104 m (122.20 in)  
Width 1.224 m (48.20 in)  
Depth 0.083 m (3.25 in)  
Overall Gross Front Area 3.800 sq m (40.90 sq ft)

Transparent Frontal Dimensions:

Length 3.021 m (118.95 in)  
Width 1.142 m (44.95 in)  
Overall Aperture Area 3.449 sq m (37.13 sq ft)

Enclosure:

Enclosure side material ANSI 6063  
Enclosure back material ANSI 3105-H26  
Frame fastening methods Screws and rivets  
Dry weight 64.0 kg (141.0 lbs)

### C. Glazing

Low iron textured and tempered glass  
Number of covers 1  
Glazing thickness - glass (in.) 0.15625  
Glazing dimensions:  
Length 3.021 m (118.95 in)  
Width 1.142 m (44.95 in)  
Surface characteristics  
Low iron, tempered, textured glass

### D. Insulation

Back insulation  
Material Fiberglass  
Thickness 25 mm (1.0 in)  
K-factor 0.3  
Back insulation  
Material Foil-faced Polyisocyanurate  
Thickness 25 mm (1.0 in)  
K-factor 0.154

### E. Absorber Plate and Piping

Materials Copper  
Absorber plate/fin dimensions:  
Length 2.883 m (113.50 in)

Width 1.159 m (45.63 in)  
Area 3.341 sq m (35.961 sq ft)  
Absorber plate or fin thickness 0.203 mm (0.008 in)  
Absorber coating Black Chrome  
Glazing to absorber air gap 20.1 mm (0.79 in)  
Flow pattern Parallel (Harp Design)  
Header tube OD 28.6 mm (1.13 in)  
Header tube thickness 3.175 mm (0.125 in)  
Riser tube OD 0.6 mm (0.03 in)  
Riser tube thickness 1.270 mm (0.050 in)  
Number of riser tubes = 10  
Riser tube/header connection = Weld  
Bond between riser and fin/plate= Ultrasonic Seam Weld

#### *F. Absorber Coating and Performance*

Black Chrome (EC Series): The absorber coating shall be black chrome on nickel with a minimum absorptivity of 95 percent and a maximum emissivity of 12 percent. The instantaneous efficiency of the collector shall be a minimum Y-intercept of 0.735 and a slope of no less than  $-0.730 \text{ BTU/ft}^2\text{-hr-F}$ . Moderately Selective Black Paint (EP Series): The absorber coating shall be a moderately-selective black paint with a minimum absorptivity of 94 percent and a maximum emissivity of 56 percent. The instantaneous efficiency of the collector shall have a minimum Y-intercept of 0.726 and a slope of no less than  $-0.910 \text{ BTU/ft}^2\text{-hr-F}$ .

#### *G. Working Fluids*

Dry weight: 64.0 kg (141.0 lbs)  
Fluid capacity: 4.54 l (1.20 gal)  
Heat transfer fluid: Water (density  $1000 \text{ kg/m}^3$ )  
Specific heat ( $\text{J}/(\text{g}\cdot\text{deg C})$ ) 4.186  
Recommended fluid flowrate  $0.076 \text{ kg/s}$  (1.20 gpm)  
Operating pressure 552 kPa (80 psi)  
Test pressure 1103 kPa (160 psi)