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Experimental investigation of the performance of a Parabolic Trough Collector (PTC) installed in Cyprus

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***Abstract*-- In this paper the performance of a Parabolic Trough Collector located at the Archimedes Solar Energy Laboratory is evaluated. It has an aperture area of 14.4 m^2, a concentration ratio of 13.7 and can be operated up to 200°C. The collector aperture is 1208 mm and the receiver pipe is stainless steel 304 L with a diameter of 28mm, coated with selective coating (absorptance: 0.93, emitance: 0.18). The collector in orientated with its axis in the E-W direction tracking the sun in the N-S direction. The advantages of this tracking mode are that very little collector adjustment is required during the day and the full aperture always faces the sun at noon. A programmable tracking system is responsible for keeping the collector focused at all times. The collector is connected to a 300 liters hot water storage tank. The water is pressurized to avoid boiling in the receiver. The performance obtained is very satisfactory and agrees with the performance curve given by the manufacturer.**

***Index Terms*—Concentrating collectors, parabolic trough collectors, performance testing, sun tracking.**

I. NOMENCLATURE

A_a	Gross collector aperture area, m^2
A_r	Receiver area, m^2
C	Concentration ratio
c_1	First-order coefficient of the collector efficiency (W/m^2-°C)
c_2	Second-order coefficient of the collector efficiency (W/m^2-°C^2)
c_p	Specific heat capacity, J/kg-K
F_R	Heat removal factor
G_B	Solar beam radiation, W/m^2
m	Mass flow rate, kg/s
Q_u	Rate of useful energy collected, W
T_a	Ambient temperature, K
T_i	Collector inlet temperature, K
T_o	Collector outlet temperature, K
U_L	Overall heat loss coefficient, W/m^2-K

Greek

η	Collector thermal efficiency
η_o	Collector optical efficiency
ΔT	Temperature difference [$=T_i-T_a$], K

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II. INTRODUCTION

A parabolic trough collector (PTC), as shown in Fig. 1, is made by bending a sheet of reflective material into a parabolic shape. A metal black pipe, covered with a glass tube to reduce heat losses, is placed along the focal line of the receiver. When the parabola is pointed towards the sun, the parallel rays incident on the reflector are reflected and focused onto the receiver tube. The concentrated radiation reaching the receiver tube heats the fluid that circulates through it, thus transforming the solar radiation into useful heat. It is sufficient to use a single axis tracking of the sun and thus long collector modules are produced [1, 2].

The receiver of a parabolic trough collector is linear. Usually a tube is placed along the focal line to form an external surface receiver (see Fig. 1). The size of the tube, and therefore the concentration ratio, is determined by the size of the reflected sun image and the manufacturing tolerances of the trough. The surface of the receiver is typically plated with selective coating that has a high absorptance for solar irradiation but a low emittance for thermal radiation.

A glass cover tube is usually placed around the receiver tube to reduce the convective heat loss from the receiver, thereby further reducing the heat loss coefficient. A disadvantage, resulting from the use of the glass cover tube, is that the reflected light from the concentrator must pass through the glass to reach the receiver, adding a transmittance loss of about 0.9, when the glass is clean. The glass envelope usually has an anti-reflective coating to improve transmissivity. One way to further reduce convective heat loss from the receiver tube and thereby increase the performance of the collector, particularly for high temperature applications, is to evacuate the space between the glass cover tube and the receiver. The total receiver tube length of PTCs is usually from 25 m to 150 m.

Parabolic trough collectors are the most mature solar technology to generate heat at temperatures up to 400°C for solar thermal electricity generation or process heat applications. The biggest application of this type of system is the Southern California power plants, known as Solar Electric Generating Systems (SEGS), which have a total installed capacity of 354 MWe [3]. SEGS I is 14 MWe, SEGS II-VII are 30 MWe each and SEGS VIII and IX are 80 MWe each.

New developments in the field of parabolic trough collectors aim at cost reduction and improvements of the technology. In one system the collector can be washed automatically thus reducing drastically the maintenance cost, which is the mostly used process required [1].

Cyprus does not have any sources of energy and depends exclusively on imported oil for its energy needs. The only inexhaustible natural source of energy that Cyprus poses abundantly is solar energy. It is well known that other forms of renewable energy, like the wind energy, wave energy and biomass have limited potential in Cyprus. Solar energy can be converted directly to electrical energy using photovoltaic panels or to thermal energy using a large variety of thermal solar collectors. The type of collectors to use in each application depends on the operating temperature of the process to connect on the solar system. Cyprus Government decided to erect a solar thermoelectric power generation station with a capacity of about 50 MW, which is a very correct movement since the development of large scale photovoltaic parks would be a very expensive solution. The collector system to be used in this case is most probably the parabolic trough, so it is very important to have a collector of this type installed and examined under the prevailing weather conditions of the island.

The purpose of this paper is to present the collector erected at the premises of the Cyprus University of Technology and the performance evaluation of the collector. This is the first time a parabolic trough collector is installed on the island and the findings should prove valuable for future uses of this type of collector.

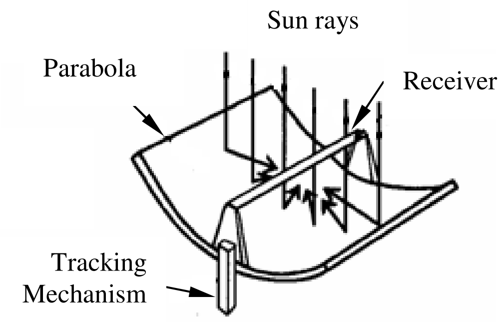

Fig. 1. Schematic of a parabolic trough collector

III. COLLECTOR SYSTEM DESCRIPTION

The collector is installed at the Cyprus University of Technology and in particular at the Archimedes Solar Energy Laboratory, which is located at the roof of the Mechanical Engineering Department of the university. The collector is supplied from the Australian company NEP-SOLAR and has the characteristics presented in Table 1.

The collector installed has a length of 12.2 m and consists of galvanized steel mounts, lightweight, stiff and precise parabolic reflector panels manufactured from reinforced polymeric material, a structurally efficient galvanized steel torque tube, a tubular receiver and an accurate solar tracking system.

TABLE I
CHARACTERISTICS OF THE COLLECTOR INSTALLED AT ARCHIMEDES SOLAR ENERGY LABORATORY

Parameter	Value
Collector Length	1993 mm
Collector width	1208 mm
Parabola focal distance	647 mm
Mirror reflectivity	93.5%
Receiver material	Stainless steel 304 L
Receiver external diameter	28 mm
Receiver internal diameter	25 mm
Glass tube transmittance	0.89
Selective coating absorptance	0.93
Selective coating emittance	0.18

The collector is orientated with its axis in the East-West direction. The advantages of this tracking mode are that very little collector adjustment is required during the day and the full aperture always faces the sun at noon. A dedicated computer-operated tracking mechanism is responsible for keeping the collector focused at all times. The motor of the tracking system is shown in Fig. 2, showing also the central support of the collector.

Photos of the collector installed are shown in Fig. 3. The photo at the left is with the collector at the focus position during operation and the photo on the right is for the collector at the park position. In this second photo the use of the flexible connectors at each side of the collector are clearly shown.

Fig. 2. Photo of the motor of the tracking system and central support of the collector (at park position).

Fig. 3. Photos of the PTC (a) on focus position , (b) at park position

The collector is connected to a hot water storage tank which has a capacity of 300 litres. The collector fluid used in the tests is water, which is pressurized to avoid boiling in the receiver. The complete plumbing circuit schematic is shown in Fig. 4 whereas a photo of the storage tank is shown in Fig. 5. As can be seen provisions are made to connect the system to the storage tank and to any other process for future experiments planned.

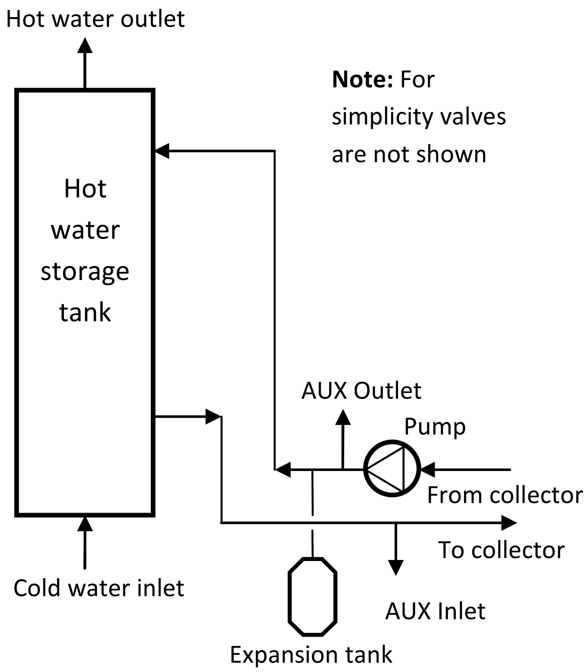

Fig. 4. Schematic diagram of the collector circuit

Fig. 5. Photo of the storage tank

IV. COLLECTOR THERMAL EFFICIENCY

The thermal performance of solar collectors can be determined by experimental performance testing under control conditions. In general, experimental verification of the collector characteristics is necessary in order to determine the thermal efficiency of the collector.

There are a number of standards, which describe the testing procedures for the thermal performance of solar collectors. The most well-known are the ISO 9806-1:1994 [4] and the ANSI/ASHRAE Standard 93:2010 [5]. These can be used to evaluate the performance of both flat-plate and concentrating solar collectors. The thermal performance of a solar collector is determined partly by obtaining values of instantaneous efficiency for different combinations of incident radiation, ambient temperature and inlet fluid temperature. This requires experimental measurement of the rate of incident solar radiation falling onto the solar collector as well as the rate of energy addition to the transfer fluid as it passes through the collector, all under steady state or quasi-steady state conditions.

ISO 9806-1:1994 and ASHRAE Standard 93:2010 give information on testing solar energy collectors using single-phase fluids and no significant internal storage. The data can be used to predict the collector performance in any location and under any weather conditions where load, weather and insolation are known.

For steady state testing, the environmental conditions and collector operation must be constant during the testing period. For the concentrating collector tests, the following parameters need to be measured:

- Beam solar irradiance at the collector plane, G_B
- Ambient air temperature, T_a
- Fluid temperature at the collector inlet, T_i
- Fluid temperature at the collector outlet, T_o
- Fluid flow rate, $\dot{m}$

In addition, the gross collector aperture area, A_a, is required to be measured with certain accuracy. The collector efficiency, based on the gross collector aperture area is given by:

$$\eta = \frac{\dot{m}c_p(T_o - T_i)}{A_a G_B} \tag{1}$$

The collector performance test is performed under steady-state conditions, with steady radiant energy falling on the collector surface, steady fluid flow rate and constant wind speed and ambient temperature. When a constant inlet fluid temperature is supplied to the collector, it is possible to maintain a constant outlet fluid temperature from the collector. In this case, the useful energy gain from the collector is calculated from:

$$Q_u = \dot{m}c_p(T_o - T_i) \tag{2}$$

The useful energy collected from a concentrating solar collector is also given by [1]:

$$Q_u = F_R\left[G_B\eta_o A_a - A_r U_L(T_i - T_a)\right] \tag{3}$$

Moreover, the thermal efficiency is obtained by dividing Q_u by the energy input ($A_a G_B$). Therefore:

$$\eta = F_R\eta_o - \frac{F_R U_L(T_i - T_a)}{CG_B} \tag{4}$$

It should be noted that in concentrating collectors the beam radiation is used G_B as these collectors can utilize only this type of radiation [2].

For a collector operating under steady irradiation and fluid flow rate, the factor F_R and U_L are nearly constant. Thus, Eq. (4) plots as a straight line on a graph of efficiency versus the heat loss parameter $(T_i - T_a)/G_B$ as shown in Fig. 6. The intercept (intersection of the line with the vertical efficiency axis) equals to $F_R n_o$. The slope of the line, i.e., the efficiency difference divided by the corresponding horizontal scale difference, equals to $-F_R U_L/C$.

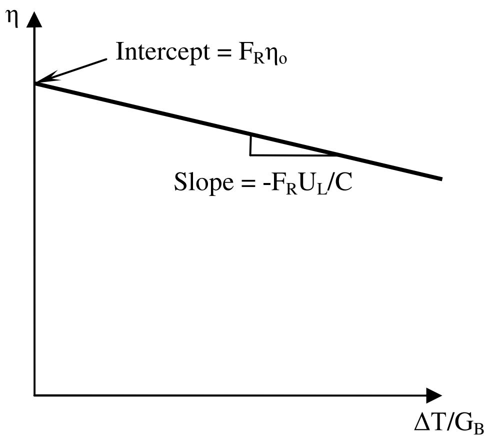

Fig. 6. Typical performance curve of a concentrating solar collector

If experimental data of collector heat delivery at various temperatures and solar conditions are plotted, with efficiency as the vertical axis and $\Delta T/G_B$ is used as the horizontal axis, the best straight line through the data points correlates the collector performance with solar and temperature conditions. The intersection of the line with the vertical axis is where the temperature of the fluid entering the collector equals the ambient temperature, and collector efficiency is at its maximum. The results of this experimental procedure for the collector installed are shown in Fig. 7. As can be seen the first order performance equation obtained is given by:

$$\eta = 0.6481 - 0.4832\frac{\Delta T}{G_B} \tag{5}$$

It should be pointed out that the slope of the concentrating collector performance curve is much smaller than the one for the flat plate ones. This is because the thermal losses are inversely proportional to the concentration ratio, C, as shown in Eq. (4). This is the greatest advantage of the concentrating collectors, i.e., the efficiency of concentrating collectors remains high at high inlet temperature; this is why this type of collectors is suitable for high temperature applications.

In reality, the heat loss coefficient U_L in Equation (4) is not constant but is a function of collector inlet and ambient temperatures. Therefore:

$$F_R U_L = c_1 + c_2(T_i - T_a) \tag{6}$$

Applying Equation (6) in Equation (3) we have:

$$Q_u = F_R\left[G_B\eta_o A_a - A_r c_1(T_i - T_a) - A_r c_2(T_i - T_a)^2\right] \tag{7}$$

Therefore, the efficiency can be written as:

$$\eta = F_R\eta_o - \frac{c_1(T_i - T_a)}{CG_B} - \frac{c_2(T_i - T_a)^2}{CG_B} \tag{8}$$

By applying this method of testing the curve obtained is as shown in Fig. 8.

As shown in Fig. 8 the second order performance equation of the collector is:

$$\eta = 0.6289 - 0.1887\frac{\Delta T}{G_B} - 2.7069\frac{\Delta T}{G_B}^2 \quad (9)$$

As can be seen from both Figs 7 and 8 the testing is not performed at high collector inlet temperatures, so these results can be considered as preliminary. The circles shown in Fig. 8 represent the values given by the manufacturer, so the performance of the collector can be considered as valid and in conformity to the performance equation given by the manufacturer.

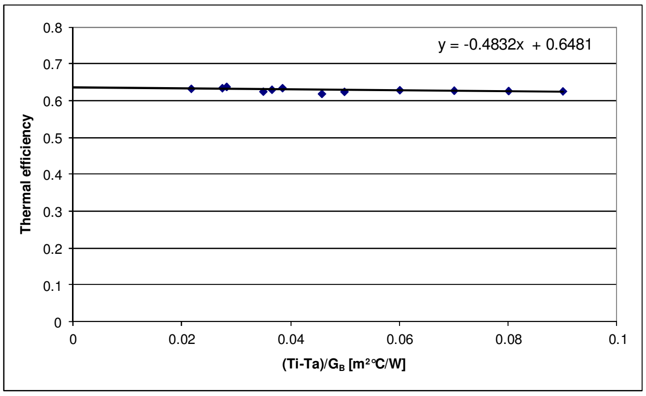

Fig. 7. First order performance curve of the collector installed at Archimedes Solar Energy Laboratory

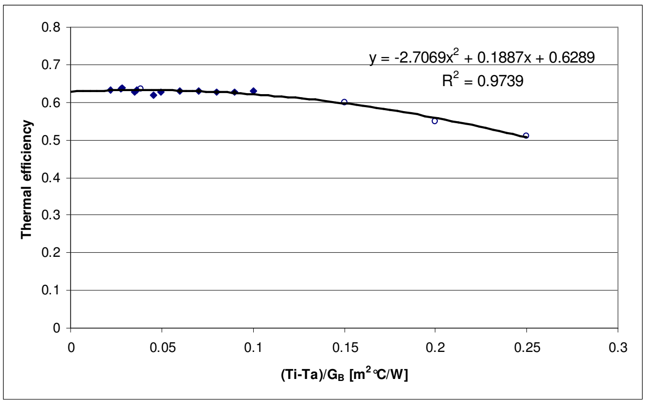

Fig. 8. Second order performance curve of the solar collector installed at Archimedes Solar Energy Laboratory

V. Conclusions

The collector installed at the Archimedes solar energy laboratory is first presented as well as the complete plumbing system. The measurements performed concern the instantaneous values of solar beam radiation, ambient temperature, collector inlet and outlet temperatures, and mass flow rate. It should be noted that this type of collector, because of the concentration, utilize only beam radiation. The collector performance was obtained by estimating the collector efficiency at various inlet fluid temperatures. By plotting the collector efficiency against the temperature rise (inlet minus ambient temperature) divided by the beam solar radiation, a straight line is obtained. The basic parameters obtained from this performance testing are the intercept and slope of the collector performance line. A second order performance curve is also obtained from the same results. Both show a satisfactory performance.

VI. References

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VII. Biographies

Soteris A. Kalogirou was born in Trachonas, Nicosia, Cyprus on November 11, 1959. He is a Senior Lecturer at the Department of Mechanical Engineering and Materials Sciences and Engineering of the Cyprus University of Technology, Limassol, Cyprus. He received his HTI Degree in Mechanical Engineering in 1982, his M.Phil. in Mechanical Engineering from the Polytechnic of Wales in 1991 and his Ph.D. in Mechanical Engineering from the University of Glamorgan in 1995. In June 2011 he received from the University of Glamorgan the title of D.Sc. He is Visiting Professor at Brunel University, UK and Adjunct Professor at the Dublin Institute of Technology (DIT), Ireland. For more than 25 years, he is actively involved in research in the area of solar energy and particularly in flat plate and concentrating collectors, solar water heating, solar steam generating systems, desalination and absorption cooling.

He has 41 books and book contributions and published 264 papers; 109 in international scientific journals and 155 in refereed conference proceedings. Until now, he received more than 4000 citations on this work and his h-index is 35. He is Deputy Editor-in-Chief of Energy, Associate Editor of Renewable Energy and Editorial Board Member of another eleven journals. He is the editor of the book Artificial Intelligence in Energy and Renewable Energy Systems, published by Nova Science Inc., co-editor of the book Soft Computing in Green and Renewable Energy Systems, published by Springer and author of the book Solar Energy Engineering: Processes and Systems, published by Academic Press of Elsevier.

Gregoris P. Panayiotou was born in Limassol, Cyprus on February 18, 1983. He graduated from the Technological Educational Institute of Athens first of his class as an Energy Technology Engineer in 2007. He had his MSc in Energy in Heriot-Watt University, Edinburgh where he graduated in 2008 with Distinction.

He is currently employed at Cyprus University of Technology as a Research Associate in a nationally funded project concerning the study and the deeper understanding of the thermosiphonic phenomenon that occurs in solar water heating systems that operate thermosiphonically.

In the past he had also worked in two research projects. The first project was funded by the Research Promotion Foundation of Cyprus and concerned the categorization of buildings in Cyprus according to their energy performance. The second project concerned the application and evaluation of advanced absorber coatings for parabolic trough collectors.

The main simulation tool he had used in most of his work is TRaNsient SYstem Simulation (TRNSYS) while he had also worked with HOMER and PVSyst.

He currently has 9 Journal publications and 12 Conference publications and his special fields of interest include wide range applications of Renewable Energy Sources systems and Energy Efficiency in buildings.