

Extended summary

Design, Test and Mathematical Modeling of Parabolic Trough Solar Collectors

Curriculum Energetica

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Abstract. Parabolic Trough Collectors are widespread in CSP applications. Their adoption is less developed in industrial heat demand applications. In the present thesis the design and test of two prototypes of PTC for the thermal loads in the range 80 - 250 °C is described. A mathematical model has also been developed to predict optical efficiency and thermal losses for any PTC. The model has been validated through comparison with the experimental results on the prototypes. Then it has been included in a custom-built simulation environment to predict yearly performances of a PTC field coupled with an industrial process heat demand. Energetic results are shown and final considerations are drawn for this application.

Keywords. Solar thermal energy, parabolic trough collector (PTC), industrial heat demand (IHD), mathematical model.

1 Introduction

Solar radiation at its origin is a high-exergy energy source: the Sun has an irradiance of about 63 MW/m². But on the Earth's surface solar energy flow dramatically decreases down to around 1 kW/m² [1]. For this reason, when high temperatures or high-exergies need to be reestablished, CSP systems are adopted. Using the principle of concentration, under proper solar fluxes, it is possible to transform solar energy into another type of energy (usually thermal) in the focus of solar thermal concentrating systems.

Among all possible geometries to realize solar concentration (central receiver systems and parabolic dishes or line-focus concentrators, such as parabolic- trough collectors and linear Fresnel collectors) parabolic through collectors are by far the most widespread technology. PTCs focus direct solar radiation onto a focal line on the collector axis where a receiver tube is installed; the fluid flowing inside the tube absorbs concentrated solar energy from the tube walls and raises its enthalpy. A solar tracking mechanism ensures that the solar beam falls parallel to the PTC axis. PTC applications can be divided into two main groups: concentrated Solar Power (CSP) plants and applications that require temperatures between 80 and 250°C [2]. The field of CSP is now a well-defined market: several commercial collectors for such applications have been successfully tested under real operating conditions. The second field, that contains mainly industrial process heat (IPH), lowtemperature heat demand with high consumption rates (domestic hot water, DHW, space heating and swimming- pool heating) and heat-driven refrigeration and cooling, has been addressed only in the recent past, and the number of commercial proposals is still very limited. For this reason a research project has been started at Dipartimento di Ingegneria Industriale of Università Politecnica delle Marche (PTC.project) for the study of the application of PTCs to IPH, DHW and all other heat demands in the mentioned temperature range. The basic bullets of the projects were de- fined as studying water and heat transfer oil as working fluids and working in an operative temperature range from 80 to 250°C. The results of the work are the design and manufacture of two prototypes "Univpm.01" and "Univpm.02" and a test bench to determine PTCs performance with water and heat transfer oil as working fluids in a temperature range up to 150°C. After the realization of the first tests on the prototypes also a mathematical model able to determine the performance of a given PTC has been developed. Finally the model has been applied to a simulated process heat demand profile in a precise geographical location (necessary to define meteorological data). The result of this work is the complete knowledge of the performance characteristics of a particular PTC during an entire year and also the information related to its interaction with a particular heat demand load.

2 Design and manufacture of PTC prototypes

Two of the most important factors affecting the efficiency of a PTC are the geometry of the parabolic shape of the modules and the accuracy of the angle of the incident solar beams [3]. In CSP plants the two key issues of accuracy in the shape and torsional resistance of each line are usually solved by two different solutions:



- a metallic frame, running through each line provides the necessary torsional rigidity to hold each module at the right angle;
- an accurate parabolic shape is obtained by small (typically 1.5 m2) pre- shaped glass or metal mirrors anchored to the frame.

In the case of a parabolic chord between 4 and 6 m (that is common in CSP applications) this method has several advantages [4]. But this approach is time consuming and expensive. For smaller values of the chord (0.5 to 2.5 m) it is useful to adopt a structure that realizes both the parabolic shape and the frame, thus having a very accurate parabolic profile and a highly resistant mechanical structure. Other authors have successfully tested the use of re-inforced fiberglass to realize the parabola of solar concentrators [5]. Following this line, in the present project, two PTC prototypes ("Univpm.01" and "Univpm.02") have been realized with a sandwich composite of fiberglass and extruded polystyrene.

2.1 PTC prototypes Univpm.01 and Univpm.02

Univpm.01 is a small PTC prototype: it presents a focal length of 0.25 m and its concentration ratio can reasonably range between 5 and 10 (depending on the receiver's diameter). It has been realized with the main purpose of verifying the design concept and acquire experience on the manufacture procedure. Its main characteristics are reported in Tables 1 and 2. Its structure is a composite sandwich made of an external fiberglass shell and an internal matrix of extruded polystyrene. Is has been manufactured with a hand lay-up process. The reflective surface is a sheet of anodized aluminum [reference] with high reflectance and special costing to enhance its resistance to outdoor conditions (water, dust, etc.).

To correct some shortcomings of the first prototype, a second one has been designed and manufactured. Univpm.02 has about twice the size of Univpm.01; since it can mount the same receivers, its concentration ratio is doubled with respect to the previous prototype. This allows a better thermal efficiency. As its predecessor, the structure has been realized with a sandwich composite; low density polyvinyl chloride has been used instead of extruded polystyrene, to increase structural performances, and also the layering has been slightly modified. But the main difference is that it has been realized with a vacuum assisted resin transfer method instead than with hand lay-up; Table 1 reports the main characteristics of Univpm.02.

	Univpm.01	Univpm.02	
Focal distance	0.25	0.55	m
Rim angle	π/2	π/2	rad
Parabola length	2.10	2.2	m
Aperture area	1.85	5.78	m^2
Total thickness of sandwich	0.05	0.05	m

Table 1. Characteristics of the Univpm.01 and Univpm.02 prototypes

2.1.1 Receiver

The receiver adopted is an aluminum pipe of circular section; the outer surface is painted with a black high temperature resistant paint. It is contained in a low iron glass cover (the same glass adopted in evacuated tube collectors). Three Teflon rings hold the glass in place





Figure 1. Picture of Univpm.01 and its hydraulic circuit for tests



Figure 2. 3D drawing of Univpm.02

on the aluminum receiver. Small holes have been drilled on the rings to allow little circulation of air inside the annulus and avoid water condensation on the glass. Dimensions of the receiver are reported in Table 2. The same type of receiver ahs been adopted on both prototypes.

Table 2. Characteristics of the receivers

Inner aluminum diameter	25	mm
Outer aluminum diameter	30	mm
Inner glass diameter	46	mm
Outer glass diameter	48	mm
Receiver length	2.60	m
Receiver external surface	0.25	m ²

2.2 Tests and results

The efficiency of a PTC can be expressed as a straight line, dependent upon a single variable:

$$\eta = F_r \eta_o - \frac{F_r U_l}{C} \frac{T_{f,in} - T_{amb}}{DI} = q + mT^* \tag{1}$$

Tests on prototype Univpm.01 with water in a temperature range from 25 to 80°C have allowed to extrapolate the following expression for eq. 1:

$$\eta = 0.700664 - 0.86590 \cdot T^* \tag{2}$$

The equation found is similar to those calculated by other researchers [5]. The line of eq. 2 and the experimental points from which it has been regressed are reported in Fig. 3.





Figure 3. Experimental values and regressed line as a function of temperature T* from tests on Univpm.01

3 Mathematical model of a PTC and annual performance simulation

A theoretical model of the optical efficiency and of the thermal losses of a PTC has been developed. Even if performances of a PTC can be obtained through tests, the experimental approach is not completely satisfying if an optimization is to be obtained. In fact, the efficiency line obtained by tests describes only overall efficiency and does not indicate thermal losses and optical efficiency. A mathematical model instead, can describe every detail of the PTC: all heat fluxes can be calculated and therefore all temperatures can be known. Also different sources of optical inefficiencies can be distinguished.

Furthermore, if a mathematical model is coupled with a reference meteorological year and an annual heat demand profile, then it is possible to calculate the interaction between a PTC field and a specific thermal load for a given location (to which the meteorological data refer).

3.1 Mathematical model for a PTC

The mathematical model that has been developed is composed of two different parts: an optical model and a thermal model.

3.1.1 Optical model

The optical efficiency is defined as the ratio between the energy that is absorbed by the receiver and the energy that hits the aperture surface of the collector. It depends on several factors: the optical properties of the used materials, the geometry of the concentrator and of the objects surrounding it and factors that describe differences between an ideal PTC and real components not accounted for in the properties of materials (such as imperfection on geometrical profiles or tracking errors).

An expression for the optical efficiency of a PTC is [6, 7]:

$$\eta_o = \rho_c(\tau_v \alpha_r)_{eff} \gamma[(1 - A_f \tan \theta) \cos \theta]$$
⁽³⁾



where:

- $-\theta$ = angle of incidence of the sun's rays on the collector aperture, rad; it is measured from the normal to the aperture plane;
- ρ_c = average specular reflectance of the receiver's reflective surface, dimensionless;
- τ_v = transmissivity of the glass;
- α_r = absorbance of the receiver's surface, dimensionless;
- $-\gamma$ = instantaneous intercept factor, dimensionless;
- A_f = geometrical reduction factor, dimensionless.

3.1.2 Thermal model

The thermal model describes all the heat losses on the receiver. It is basically a set of equations applied to different parts of the receiver itself. The thermal model, together with the optical model allows to calculate the energy transferred to the fluid for any given working and ambient condition.

The heat fluxes considered are reported in Fig. 4. These fluxes have been represented with the following set of balance equations:

$$\begin{cases} \tau_v \alpha_r Q_{rcr} = Q_{kr} + Q_{crv} + Q_{rrv} \\ Q_{kr} = Q_{crf} = Q_f \\ Q_{crv} + Q_{rrv} = Q_{kv} \\ Q_{kv} + \alpha_v Q_{rcr} = Q_{cva} + Q_{rvc} \end{cases}$$
(4)

Subscripts in equations have the following meaning:

- the first letter indicates the type of heat transfer mode: k for conduction, c for convection and r for radiation;
- the second letter indicates the element of the system from which the flus originates (in accordance with the verses of vectors in Fig. 4);
- the third letter indicates the element of the system to which the flux arrives (in accordance with the verses of vectors in Fig. 4);

In the case of conductive heat transfer the third letter is omitted.





Figure 4. Cross section of the receiver with heat fluxes

3.2 Annual simulation of performances

As stated, once the model has been completed and validated though comparison with the experimental results, it has been introduced in a custom-built simulation environment in order to run annual simulations of performance for a field of PTCs applied to a heat demand load.

A reference meteorological year has been defined for the location of Ancona (Italy) [8,9], that comprehends hourly values of ambient temperature, relative humidity, wind speed and solar radiation data (DNI and GHI). Then a heat demand profile has been defined, that includes hourly values for:

- inlet fluid temperature in the PTCs;
- mass flow rate through the receiver;
- indication whether or not the process is demanding heat;

Starting from these indications and considering a 50 m² aperture surface PTC field, the values of useful heat produced by the filed for a temperature of 150°C and working with heat transfer oil as circulating fluid has been calculated. Also the total amount of available energy hitting the aperture area has been defined and the value of the maximum producible energy. These results are shown in Fig. 5 and Fig. 6 in the form of cumulative function and monthly totals, respectively.



Figure 5. Monthly total collected energies; Edir=total fallen energy, Eprod=total producible and Eu = useful



Figure 6. Summation of energies through the hours of the TMY for the 50 m² PTC field. Blue=total fallen energy, violet=total producible and yellow = useful

4 Conclusions and remarks

The present thesis is mainly a description of the activities carried within PTC.project research. Since the project is still running, some results are temporary or need further investigation and study. But many of the original intents have been accomplished; in particular:

- two prototypes have been built and on of them has been tested;
- a new test bench to perform tests with heat transfer oil and water as working fluids and with working temperature range from 10 to 150°C has been designed and partially realized;
- a mathematical model of a PTC has been developed that accounts for optical efficiency and thermal losses;
- a simulation environment to perform yearly simulations of a PTC field coupled with a heat demand profile has been realized and applied.



No economic considerations have been drawn for the moment, but the analysis of the energetic results and the experience acquired suggest that PTC are a mature technology that will play and important role in the near future.

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