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Design, manufacture, and test of a prototype for a parabolic trough collector for industrial process heat

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ABSTRACT

The manufacture of low-cost parabolic trough collectors (PTCs) for industrial process heat applications ranging from 70 to 250 °C is crucial for the widespread availability of this solar technology. Thus, we present a prototype of a PTC with a 90° rim angle and a small concentration ratio of 9.25 built in fiberglass and extruded polystyrene, called UNIVPM.01. Fiberglass is used as the external shell and extruded polystyrene as the inside fill component. The receiver is an aluminum pipe of circular cross-section, contained within a low-iron glass envelope. The tracking system is based on a solar-position computer program. The main features of this prototype are its cost-effectiveness, low weight, high mechanical resistance, and ease of manufacture. First, we show the design and manufacturing process in detail. Then, we describe the test bench used to evaluate the collector thermal efficiency. Tests were performed following the directives of ASHRAE Standard 93-2010 and using demineralized water for temperatures up to 85 °C. Results show that the equation for thermal efficiency is comparable to that of other similar collectors available in the literature: the intercept is 0.658 and the slope is −0.683.

1. Introduction

In OECD (Organization for Economic Co-operation and Development) countries, industry accounts for 30% of overall energy consumption. In EU (European Union) countries, two-thirds of this consists of heat rather than electrical energy. Studies confirm that about 50% of this industrial heat demand is located at temperatures of up to 250 °C: in 2000, this energy demand in the EU-15 was estimated at about 300 TWh [1]. Among solar technologies suitable for satisfying this heat demand, concentrating solar collectors such as PTCs (parabolic trough collectors) are one of the most promising.

The development of low-cost PTCs plays a decisive role in the spread of this technology. This objective can be reached only by studying and testing profoundly innovative prototype designs. For this reason, a research program called PTC.project has been started at the Marche Polytechnic University regarding the development of PTCs for industrial heat production in the range of 70–250 °C.

The systematic study of PTC design began several decades ago. In his paper of 1976, Treadwell [2] considered how optical and thermal effects influence the efficiency of a PTC. He found that rim angles of 90° minimize the maximum distance between the parabolic reflector and the focus. Since the receiver diameter is proportional to this distance, thermal losses, which are proportional to the diameter itself, are reduced.

In a detailed work published in 1992, Thomas and Guven [3] outlined the main structural design requirements for a PTC. A PTC should: a) provide and maintain the correct optical shape of the reflective surfaces; b) maintain its shape within the specified tolerances during operations; c) protect the reflective surfaces under extreme weather conditions; d) withstand long-term environmental exposure. In other words, the stresses and deflections experienced by the receiver and the reflector must remain below specified levels under gravitational, wind, and thermal loads. On the other hand, the choice of materials depends on environmental stability, durability, mechanical and physical properties, suitability of the construction method, fitness for high production rates, low total weight, and cost. The authors also state that a sandwich structure is a good design, but high precision moulds are required in order to successfully fabricate high quality PTCs.

In 1994, Kalogirou et al. [4] presented a PTC design with high stiffness-to-weight ratio and a low-labor manufacturing process. The structure is made of polyester resin and woven fiberglass cloth, with plastic conduits that provide reinforcement. In a paper published the same year [5], the authors outlined an optimization of the design based on three parameters: a) collector aperture; b) rim

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angle; c) receiver diameter. They also proposed a tracking mechanism with a control system consisting of three light-dependent resistors.

The EUROTROUGH project [6] carried out in 2001 proposed a torque box design with lower weight and less collector deformation than other designs. This technology presents different advantages: a) the possibility of connecting more collector elements on one drive, so that their number, in addition to costs and thermal losses, is reduced; b) reducing the torsion and bending increases the optical performance and wind resistance. A torque box structure was also used by Brooks et al. [7] with a mix of advanced and less sophisticated technologies to manufacture a reflector made of stainless steel sheets covered with aluminized acrylic film. This solution grants accessibility, accuracy, ease of fabrication, and cost reduction.

In 2007, Valan Arasu and Sornakumar [8] presented a simple, low-cost hand lay-up method for manufacturing PTCs based on the previous work of Kalogirou et al. [4]. The design proposed consists of a smooth 90° rim angle, reinforced parabolic trough made of layers of polyester resin and chopped strand fiberglass.

In 2011, Rosado Hau and Escalante Soberanis [9] illustrated the production of a water-heating system based on PTC technology limited to a maximum temperature of 55 °C. The collector presented uses a sheet of polished stainless steel. The receiver is a copper tube coated with a thin black paint, and shielded by a polycarbonate glass; it is not evacuated.

In their work of 2012, Venegas-Reyes et al. [10] described a light but robust structure of aluminum made only using hand tools. This PTC has a rim angle of 45° and, since it is designed for low-enthalpy steam generation and hot water, it presents an unshielded receiver without a glass cover in order to reduce costs. In another work published in 2013 [11], the authors presented five PTCs for the same purpose; three of them have a rim angle of 90° and the other two have a rim angle of 45°.

The main feature of the PTC prototype presented in this work is the parabolic support structure: it is a composite of fiberglass (used as an external shell) and extruded polystyrene (XEPS, as inside fill component). These two materials have been chosen for different reasons: a) cost; b) weight; c) resistance to atmospheric agents; d) ease of manufacturing. This solution is preferred to the simple fiberglass structure because it offers extremely high structural performances and low weight. The prototype has also been tested and has shown a performance similar to different PTCs reported on by other authors.

The present work is organized as follows. Section 2 presents the geometrical and structural characteristics of the PTC prototype. We also describe the manufacturing technique adopted to construct the collector, the tracking system used and an estimate of the initial cost. In Section 3, we illustrate the methodology and test bench used to carry out experimental investigations. The thermal efficiency and other relevant aspects useful in defining the performance of a PTC are outlined in Section 4. In Section 5.1 we provide the experimental results and a detailed comparison with other collectors available in the literature. Finally, we discuss the results obtained in Section 6.

2. Design and manufacture

Two important factors to be considered in the construction of a PTC are the accuracy of the parabolic shape and the torsional resistance of the collector [3]. Since PTCs are generally arranged in lines parallel to each other and each line is rotated in the middle, the weight of the collectors and external forces, mainly wind loads, can generate large moments on the section next to the rotating system.

These two key issues are usually solved via 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, which is obtained by anchoring small (typically 1.5 m^2) pre-shaped glass or metal mirrors to the frame.

In the case of a parabolic chord between 4 and 6 m (common in PTC plants for electric power production), this method has several advantages: e.g., the movement of small parts rather than big sections and the possibility of adjusting the position of each reflective surface with respect to the frame, which is necessary to obtain the desired accuracy on a large parabolic arch. But this approach is time consuming and expensive. For smaller chord values (0.5–2.5 m), it is useful to adopt a structure that considers both the parabolic shape and the frame, thus ensuring a very accurate parabolic profile and a highly resistant mechanical structure.

For this reason, the present project has led to a PTC prototype called UNIVPM.01 realized with a sandwich of fiberglass and extruded polystyrene. The advantage in using a sandwich lies in its mechanical properties, and fiberglass is a very common component of such composite materials.

2.1. Design of the PTC prototype

The PTC designed is quite small. It presents a focal length of 0.25 m and a rim angle ϕ_r of 90°. This particular rim-angle value was chosen to minimize slope and tracking errors [2,12].

Other characteristics of the concentrator are reported in Table 1. Since the prototype is to be used for testing, the supports for the receiver were designed to allow the position of the receiver itself to be adjusted (both in terms of height and angle with respect to the origin of the parabola). This was done in order to be able to test different receivers on the same parabolic reflector. The present study makes use of one particular receiver with the geometrical characteristics reported in Table 2. The receiver is an aluminum pipe of circular cross-section: the outer surface is painted with a black high-temperature-resistant paint. It is contained in a low-iron glass envelope (the same glass used for evacuated tube collectors). We used a receiver made of aluminum for the following reasons: it is light, ductile, and easy to be coated with paint. Bending was avoided because the PTC prototype was tested for temperatures up to 85 °C.

Three teflon rings hold the glass in place on the aluminum receiver. Small holes were drilled in the rings to allow air circulation inside the annulus and prevent condensation on the glass. A schematic of the receiver is shown in Fig. 1, while the thermal/optical properties of the materials used are provided in Table 3.

With such a receiver, the concentration ratio C, i.e., the ratio between the aperture area of the collector A_a and the absorber outer surface A_r, is [14]:

Table 1
Characteristics of the UNIVPM.01 concentrator.

Characteristic	Symbol	Value
Focal length (m)		0.250
Length (m)		2.100
Aperture (m)		1.000
Mirror length (m)	L_c	2.000
Mirror aperture (m)		0.925
Aperture area (m^2)	A_a	1.85
Total sandwich thickness (m)		0.050
Rim angle (°)	ϕ_r	90