Concentrated Solar Collector With Black Enameled Receiver Tube

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ABSTRACT:

Nowadays, the industrial sector is strongly attracted by potentialities offered by renewable energies, in particular by the solar thermal systems, since they are able to produce both heat at different temperature levels and cooling energy, through the coupling of the solar plant with an absorption chiller.

In recent years, research activities have been oriented to the development of solar collectors able to generate heat at temperatures useful both for industrial processes for the energy supply to an absorption chiller and cooling energy production (about 200°C). For that purpose, Parabolic Trough Collector (PTC) prototypes with tube receivers coated with an enamel-based selective surface, have been designed at the Faculty of Engineering of the University of Florence for the process heat production at a temperature in a range of 100-250°C and for Solar Heating & Cooling applications (SHC).

Presently two different parabolic trough collector prototypes are installed at the University of Florence (Figure 2, Figure 3 : 70 m² acceptance area and 40m of receiver tube length) and in the last two years experimental campaigns have been carried out in order to determine the actual thermodynamic performance of the solar collectors.

In this paper, the main features of PTC collectors will be illustrated, with a specific focus on the techno-economic specifications for the design of the collector and on the modeling and evaluation instruments that directed the choices to the enamel-based coating with high absorptance. Also, the process for the deposition of the enamel and for the manufacturing of the receiver tube will be described, as well as the chemical and physical characteristics of the coating.

Optical measurements were done on the coating in order to evaluate the performance. The results allowed comparisons of the enamel-based coating with other technological solutions available on the market and to provide preliminary estimates of the expected thermodynamic performance of the receiver tubes.

Results of the experimental campaigns are presented in this paper along with a comparative analysis of the real performance of the enamel-based coating with the alternative solutions in the market in technical and economic terms.

Introduction

Solar radiation is a high-temperature and high energy source that may be exploited by using concentrating solar systems which transform solar energy into another type of energy (usually thermal). Solar concentrating systems are classified by their focus geometry as either point-focus concentrators (central receiver systems and parabolic dishes) or line-focus concentrators (parabolic-
trough collectors (PTCs) and linear Fresnel collectors [1].

PTCs focus direct solar radiation onto a focal line on the collector axis. A receiver tube with a fluid flowing inside absorbs concentrated solar energy from the tube walls and raises its internal energy is installed in this focal line. The collector is provided with one-axis solar tracking to ensure that the solar beam falls parallel to its axis. PTCs can only use direct solar radiation called beam radiation or Direct Normal Irradiance (DNI), i.e., the fraction of solar radiation which is not deviated by clouds, fumes or dust in the atmosphere and that reaches the Earth’s surface as a parallel beam.

PTC applications can be divided into two main groups. The first are the Concentrated Solar Power (CSP) plants. Operating temperatures are between 300° and 400°C, typical aperture widths are about 6 m, total lengths are from 100 to 150 m and geometrical concentrating ratios are between 20 and 30. The other group of applications requires temperatures between 100° and 250°C. These applications are mainly industrial process heat (IPH), low-temperature heat demand with high consumption rates (domestic hot water [DHW], space heating and swimming pool heating) and heat-driven refrigeration and cooling. Typical aperture widths are between 1 and 3 m, total lengths vary between 2 and 10 m and geometrical concentrating ratios are between 15 and 20.

In recent years the Energy Engineering Dept. of the University of Florence has been focusing on the development of small-scaled PTC collectors suitable for the application in industrial processes and for the combined production of heating and cooling energy (SHC plant) [2]. A PTC collector with a tube receiver coated by an enamel-based selective surface has been designed for heat production at temperatures in a range of 100-250°C and for Solar Heating & Cooling applications (SHC) [3].

The design of the PTC geometry has been directed first to the optimization of the optical efficiency of the collectors and then to the maximization of the energy efficiency. The effect produced by deformations in the shape of the parabola as well as errors in the tracking of the sun position have been analyzed through ray-tracing analysis. Moreover, tolerance limits for the manufacturing of the PTC have been defined through the analysis of the effects of wind loading deformations.

Once the geometry of the system was defined, the design focus centered onto the selection of the selective coating for the receiver tube. Many solutions were investigated with the aim to find the best compromise among energy efficiency, manufacturing cost and durability. Among them were a multi-layer coating deposited with physical vapour deposition (PVD) techniques [4], black-chrome plated coating and an enamel-based coating [5]. They were evaluated in terms of spectral properties, adhesion and abrasion resistance, as well as corrosion to atmospheric conditions. Finally, the enamel-based coating was selected for the application onto the PTC receivers, even if the spectral properties were not optimized, due to its high corrosion and abrasion resistance and the low manufacturing cost.

Two different PTC prototypes are installed at the University of Florence (70 m² acceptance area and 40m of receiver tube length) and in the last two years experimental campaigns have been carried out in order to determine real thermodynamic performance of these solar collectors.

**PTC Collectors**

The PTC technology, since the beginning, showed the most interesting properties in terms of thermal efficiency, collected energy and, especially, of already existing know-how. PTCs have low heat losses, relatively to other collector types, even at elevated temperatures, as they concentrate solar radiation on a linear absorber whose surface area is smaller than classical ones. Heat losses
depend on the optical efficiency of the reflecting structure, on the absorber’s section area, on the materials and on the operating temperature. The higher the flow temperature is, the higher the heat losses are, even if there isn’t a linear dependence (it is approximately quadratic).

PTC collectors are characterized by three main sub-components: the concentrator reflective surface (reflector), the absorber tube (receiver) and the tracking system (Figure 1)

The reflector is usually made by one bearing structure that supports a reflecting material, selected among a list of solution available on the market (glass mirror, aluminum, silvered polymer). The bearing structure has a parabolic shape and it is designed with the appropriate stiffness to withstand wind loads and to meet the tolerances limits of manufacturing.

The tracking system is necessary because the PTC collector needs to have 1-axis moved in order to align the focal line with the beam radiation direction. Any misalignment of the PTC would entail a reduction of the optical efficiency, therefore, the tracking system should be designed to withstand wind loads and to achieve optimal efficiencies for energy gains.

The receiver is characterized by a stainless steel tube with a solar selective coating and a concentric glass tube with a higher diameter. A thermo-vector fluid flows inside the tube and extracts the reflected solar radiation transforming it into heat, while the operating temperature increases. The selective coating on the absorber improve the solar radiation absorption and the surrounding glass tube plays the role of reducing the thermal heat losses caused by the IR radiation emitted while the receiver is operating at temperature above the ambient.

The University of Florence has been involved in R&D projects (SALTO project, locally funded) focused on the development and manufacturing of PTC collectors for medium temperature applications. Design methodologies were directed towards cost reduction at fixed target prices, and the optimization of the flexional and torsional stiffness of the collectors through the combined use of steel for the supporting structure and of self-sustaining reflective materials. Two different PTC prototypes have been manufactured and installed at the University of Florence, and main features are illustrated in Table 1 and in the following Figures.

<table>
<thead>
<tr>
<th>Collector Type</th>
<th>SALTO 1</th>
<th>SALTO 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical Solution</td>
<td>Steel Structure completely made in carpentry</td>
<td>Simple steel structure with self-supporting elements</td>
</tr>
<tr>
<td>N° of Collectors</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Module Length</td>
<td>5000</td>
<td>5000</td>
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<tr>
<td>Aperture Width</td>
<td>2250</td>
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<tr>
<td>Receiver Tube Diameter</td>
<td>60,3</td>
<td>42,4</td>
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<tr>
<td>Receiver Thickness</td>
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<td>2</td>
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<tr>
<td>Glass Tube Diameter</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>Glass Tube Thickness</td>
<td>2,5</td>
<td>2,5</td>
</tr>
<tr>
<td>Mirror Type</td>
<td>Almeco Vega WR 193 (2 collectors)</td>
<td>Almeco Vega WR 193 (2 collectors)</td>
</tr>
</tbody>
</table>

Table 1 – Solar Field Test-rig installed at the University of Florence – Main features
The design methodologies highlighted good optical and tracking efficiency of the collectors while exposed to high wind loads, but especially entailed the increasing of the weight of the collectors.

Moreover, these solutions are characterized by a stiffened structure made of steel that supports a self-sustaining reflective mirror that is completely pre-assembled in a workshop. Also, the receiver tube is pre-assembled with the glass tube, and a special junction has been design for the easy implementation of the absorber pipe with the PTC.

PTCs are easily installed, because, even if many operations are required for the alignment of collectors, the assembly of components is made easier by the use of pre-assembled parts. Collectors have been designed taking into consideration the possibility offered by an SHC plant to supply both heat and cooling energy that entails higher values of the energy produced. Consequently, the solar collectors have been designed following a quite high target price (500-600 €/m$^2$), more than the cost accepted for the industrial sector (280-350 €/m$^2$).

The selection of the right coating for the absorber tube was crucial in the design of PTCs because it plays an important role in the photo-thermal conversion of the solar radiation. Solar absorber surfaces must have high solar absorptivity ($\alpha$) and low thermal emissivity ($\varepsilon$) in order to have very good photo-thermal conversion at the operating temperatures. The operating temperature reflects on the shape of the blackbody curve in the infrared region of the solar radiation. If the temperature increases, the peak moves to shorter wavelengths and increases its intensity, while, if the temperature decreases, the peak moves to longer wavelengths and decreases its intensity (Figure 4). The ideal selective coating should have the following properties:

- Solar Absorptance $\alpha > 0.95$
- Thermal Emittance at high temperature (400°C) : $\varepsilon < 0.05$
- Chemical and Thermal stability at a higher temperature than the operating one (at least 250-300°C)
- Endurance and Reliability
- Low-cost and easy to manufacture

It is very difficult to find a best compromise among the above-mentioned requirements for systems operating at medium temperature (about 200°C). At the University of Florence, design methodologies were directed towards cost reduction and for what relates the receiver. The enamel-based coating was selected due to its very high endurance and reliability and due to a manufacturing cost lower than the other solution available on the market. The enameled coating also presented very high absorptivity ($\alpha = 0.93$) even if the thermal emissivity is actually very far from the technical targets ($\varepsilon = 0.91$).

**Porcelain (Vitreous) enamels for solar receiver**

Porcelain (vitreous) enamels have been recognized as having high value as solar collector surfaces due to their high absorbance characteristics (alpha $\sim 93\%$), their high weather resistance, high mechanical resistance to sand erosion and high level of protection afforded to the substrate metal (Stainless Steel - AISI 304) against corrosion.

The cost of enamelled metals is very effective in terms of production costs and life cycle [5].

The coating was specifically formulated, by the University of Florence and Ferro Corp., to achieve the maximum absorptance as well as the other performance requirements. The ground coat base formulation utilized selected oxides specifically for solar absorption. Application of the porcelain (vitreous) enamel coating was accomplished with an electrostatic powder having a coefficient of expansion around $93-98 \times 10^{-7} \text{m/m/}1\text{°C}$ and a softening temperature around $525\text{°C}$. The stainless steel qualities are such that warping and distortion during firing (application of the enamel) at temperatures over $800\text{°C}$ is negligible.

Two different enameled receiver prototypes have been developed in cooperation with the University of Florence. The main features are listed in Table 2 and the manufacturing process is described below.

Double hanging holes for jigs were made on both extremities of the solar pipes to ease handling through the surface treatment processes. The pipes were degreased in a low temperature degreasing tunnel to eliminate surface oils and dirt before continuing on to a grit blasting process.

Grit blasting was done on a bottom chain conveyor: two turbines operated at about 2500 rpm with GL25 metallic grit. The conveyor speed was about 2 m/min. Mild grit blasting conditions were adopted to avoid deformation of the pipes, preferring a double blasting cycle to a heavy one.

Enamel application was initially made for prototypes with electrostatic guns.

The firing of tubes was done on a modern lightweight furnace and the optimized conditions for the production of the enamel were a firing-time over 3 minutes and furnace temperatures over $800\text{°C}$.

After enamelling the uncoated ends were cut down in order to allow welding together the modular
solar pipes in multiples of about 1500 mm units up to the final dimension of the solar collector field.

The quality of the enamel coating after firing was very good. The tubes presented a closed (tight) surface, good adherence (impact gun test according to ISO 4532/UNI 9613), gloss below 60 and an acid resistance of class A.

The enamel thicknesses ranged from 100 to 150 μm from end to end. The pipes were neither deformed nor bent during firing. Repairing enamel defects, if they occur, is still possible by brushing, powder application and re-firing without affecting adherence and pipe dimensional stability.

Specific tests have been carried out on samples in order to assess the optical properties for the absorber pipe depending on the coating applied (Figure 5, 5). In parallel, mathematical models have been developed in order to evaluate the energy performance of the receiver tube as a function of the optical properties of the coating, of the operating temperature and of the geometry of the tube.

![Spectral properties of coatings in the Visible range](image)

![Spectral properties of coatings in the IR range](image)

Porcelain (Vitreous) Enamel coating has been compared with other solutions available on the market (especially black-chrome plated coating) in terms of technical-economic profitability in order to identify the most competitive solution for the PTC collectors. Porcelain (Vitreous) Enamel solution highlighted very interesting results especially in terms of efficiency-to-cost ratio and, even if from the thermodynamic point of view it isn’t the highest performing solution, it has been selected for the implementation to the PTC collectors.

**Experimental Results**

For the selection of the best performing coating to be applied to the PTC prototype 2D and 3D mathematical models have been developed in order to carry out a sensitivity analysis of the energy performance as a function of the receiver tube characteristics. Particularly, the sensitivity of the mid-temperature energy performance of the absorber tube to the boundary conditions and to the optical properties of the coating has been analyzed. Through the use of mathematical models technological and economical limits have been identified for different types of coating, and the most interesting solutions have been compared in terms of energy efficiencies and yields.

The most interesting solution for the receiver tubes were the above-mentioned black-enamel (manufactured by Ferro) and a black-chrome coating (manufactured by Energie-Solaire), both deposited onto a stainless steel substrate.
A dynamic simulation model has been developed in order to compare solutions not only in energy but also in economic terms in order to identify the optimum solution for the solar field at the University of Florence (about 75 m² - Figure 7). The operating temperatures for the solar field was considered at 70°C during winter (from October to April) and 190°C during summer (from May to September).

The Black-chrome coating entailed an energy yield by the solar field of about 42930 kWh/year, while the Porcelain (Vitreous) Enamel entailed 32412 kWh/year. Nevertheless, this disadvantage is overcome by the enameled coating by its lower cost for the manufacturing (about 35%) and its long-term durability (more than 20 years). The enameled receiver cost is about 25 €/m and its durability is more than 20 years while the black-chrome cost is about 40 €/m and its durability is about 10 years.

Since the target lifetime for PTC for medium temperature applications is more than 10 years and since the target price for manufacturing is about 350 €/m², the choice for the PTC prototype at the University of Florence was directed to the enameled receiver.

Once the installation of the solar field was completed, experimental campaigns were conducted with the aim to evaluate energy performance of the system and to identify the characteristic efficiency curve for the solar collectors. During the first steps, energy loss problems were found in the connection between the receiver tube and the sustaining parabola, mainly due to an incorrect positioning of the glass tube around the absorber. For that reason, experimental data may be considered valid only for a limited temperature range (up to 100°C) since convective heat losses are not so appreciable in that operating range, and they may be neglected.

Experimental data validated the simulating model, therefore it was possible to forecast energy performance of the solar field with different type of coatings. Figure 8 highlights efficiency curves for PTC collectors with an enameled receiver tube and with a black-chromed tube.
Results highlighted that the black-chromed tube provides an efficiency of about 18% higher than the enameled at operating temperatures higher than 190°C, while for lower temperatures there is a lower distance between the efficiency curves, especially below 150°C (about 12%).

**Conclusions**

At the University of Florence a PTC prototype solar field of about 75 m² area has been installed. The absorber is characterized by a stainless steel (AISI 304) covered by a black enamel provided by Ferro Corp. with highly selective optical properties. Mathematical and dynamic models have been developed in order to estimate the performance of the absorber as a function of the coating type. Black-Chromed coatings were identified as the first competitor to the black enamel for the application to the receiver tube of a PTC for medium temperature applications. Results of simulation highlighted that, generally, the black-chromed receiver is performing better than the black enamel at all temperature levels. Nevertheless, for a temperature range of about 100-150°C, the black enamel may be considered equivalent in technical and economic terms.

The black enamel may be also applied for higher temperature applications, especially if long-term durability is necessary for the maintenance of the energy efficiency at constant levels.

A possible solution to increase the competitiveness of the black enamel up to 200°C is to cover the dark porcelain enamel with a secondary coating application of doped indium tin oxide which are very thin, being several orders of the wavelength of solar radiation. In this way it is possible to lower the emissivity of the coating down to 0.34 and to increase the energy efficiency of the PTC of about the 13% at 190°C [6]. The costs for the doping of the black enamel is very high, but if it would be maintained below 10€/m the doped black enamel will become the most competitive solution in the market for all levels of temperatures.

In conclusion, if it would be possible to find a solution for the improvement of optical properties in the IR region the black enamel will become the best solution for PTC collectors at medium temperatures: the economic competitiveness of the black enamel is directly proportional to the decreasing of its spectral emissivity.
REFERENCES