A NEW FACILITY FOR TESTING LINE–FOCUS CONCENTRATING SOLAR COLLECTORS FOR PROCESS HEAT APPLICATIONS

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Abstract

This article describes the characteristics and design aspects considered in the definition and construction of an experimental facility for testing tracking solar collectors of small size adequate for supplying thermal energy in the medium temperature range (between 100 to 250 ºC). Manufacturers of tracking solar thermal collectors need to test and to know the real performance parameters of their new designs, and the potential customer needs to have the solar collectors certificated according to standard test methods as ISO 9806:2017.

The test facility presented in this paper will meet all these needs because it fulfills the pressure, temperature, heat transfer fluid and flowrate requirements; both to evaluate the designs, and to certify the expected real performance. Additionally, this test facility will also be useful to evaluate components for hydraulic circuits of solar process heat applications up to 250 ºC.

Keywords: solar thermal systems, solar collector testing, optical–thermal performance, pressurized hot water, solar process heat applications, solar heat in industrial processes (SHIP), balance of plant

1. Introduction

The Plataforma Solar de Almería[1] (PSA), belonging to the Spanish Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), has two test facilities for testing commercial parabolic trough collectors:

- The first parabolic through collector (PTC) test loop was built at PSA in 1996. It was engineered for PTC testing up to 75 meters long, East–West oriented. This facility was used for more than fifteen years with several PTC prototypes, which were installed in successive years, reaching three different collectors in parallel.
- It became necessary to approach a new test facility due to the previous test loop reached its maximum capacity, so the second test loop was built in 2015, the Parabolic Trough Test Loop (PTTL), with capacity to operate in two solar fields simultaneously: one solar field for East–West oriented PTC prototypes up to 150 m long, and another solar field for North–South oriented PTC suitable for complete collector loops up to 600 m long (León et al, 2014).

Both test facilities were designed for large–sized PTCs using silicon–based thermal oil as heat transfer fluid up to 400 ºC of outlet temperature, and focused to large commercial PTC solar fields for electricity generation. But they are not adequate for testing small–sized collectors due to requirements regarding flowrate and pressure testing conditions.

Because the use of solar energy for the supply of thermal energy to industrial processes is a market which growth expectations are high (IEA, 2012), it has been decided to build a new experimental facility, suitable for the testing of medium temperature (100–250 °C) solar thermal collectors. Any type of line–focus tracking solar collector, either PTCs or linear Fresnel type, can be tested, including new prototypes (Pulido Iparraguirre et al, 2019) and components for the hydraulic circuit.

[1] www.psa.es

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For these applications of solar heat in industrial processes (SHIP) is more usual to use water instead of thermal or synthetic oils (heat transfer fluids, HTF), the temperature is lower, and the pressure higher, because of the different fluid, water. So, for this type of PTC, smaller, with lower capacity and with different HTF, is necessary to undertake a new facility with these features.

At PSA there have been some previous projects focused on the design, construction and evaluation of small–sized PTCs. In particular, for the CAPSOL project it was erected a small facility for the testing of two prototypes of small–sized PTCs using pressurized hot water up to 220 °C (Fernández–García et al, 2018). However, that facility is already out of work. The previous PSA's experience in the CAPSOL project and the most recent experience in the testing of large–sized collectors (Valenzuela et al, 2014) have been considered in the design of this new facility.

Although the PSA has several laboratories for testing the optical performance and reliability of components (e.g. mirrors, receiver tubes, etc.); finally, any new design of solar collector requires the testing of a complete prototype in real outdoor conditions.

2. General overview

2.1 Commercial PTCs

Many industrial processes need thermal energy in the temperature range from 60 ºC to 220 ºC, some others exceptionally up to 260 ºC (Kalogirou, 2002). The application of this range of process temperature is suitable both for direct heating, as well as for solar cooling, power generation with Organic Rankine Cycle and desalination.

There is a wide variety of commercial tracking solar collectors, with a wide range of characteristics. After the review of the main commercial collectors, that was carried out in the framework of the European project STAGE–STE[2], a compromise solution can be reached for their features, that could be summarized as follows:

- Aperture width: up to 3 meters.
- Aperture length: from 2 to 5 meters, some of them up to 20 meters.
- Temperature: from 130 ºC to 230 ºC.
- Thermal power delivered per unit: from 2 to 16 kW, some of them up to 150 kW.

2.2 Standards for testing

The test facility presented in this article will fulfill the current standards for solar thermal collectors testing (Fernández–García et al, 2018): ASTM E905–87:2013, SRCC 600 2014–17:2015 and ISO 9806:2017. The standard EN 12975–2:2006 is already withdrawn and substituted by ISO 9806:2017. All parameters will be measured with the required accuracy.

The most restrictive required uncertainty of cited above standards for each parameter are shown in the Table 1, together with the uncertainty available in the installation.

Tab. 1: Most restrictive required accuracy of the standard, and accuracy available in the new PSA's test facility

Parameter	Standard	PSA's test facility
Mass flowrate	≤ 1.0 % (all standards)	0.1 %
Inlet water temperature	≤ 0.2 ºC (ISO 9806:2017)	±0.1 ºC to 0.525 ºC (0 ºC to 250 ºC)
Differential water temperature	< 0.05 ºC (ISO 9806:2017)	±0.2 ºC to 1.05 ºC (0 ºC to 250 ºC)

[2] www.stage–ste.eu

2.3 Water vs silicon based HTF

The use of water as HTF has some advantages over thermal or synthetic oils. Water is environmental friendly and the facilities do not need ATEX requirements, which are required when thermal oils are used. On the other hand, the installations need to be designed for higher pressure, that is affordable by existing commercial equipment if very high temperatures are not reached (up to 220 ºC to 250 ºC). So, water is more suitable for these type of collectors.

3. Test facility features

The main features of the new solar collectors' test facility are the following:

- Heat transfer fluid: pressurized hot water (environmental friendly fluid).
- Operation manometric pressure: up to 4.2 MPa.
- Operation temperature: up to 250 ºC.
- Operation flowrate: from 0.05 to 0.5 $kg \cdot s^{-1}$.
- Expected size of the solar collectors tested: up to 25 m^2 per collector unit.
- Material used for the hydraulic circuit: stainless steel.
- Field length: up to 40 m, in both orientations: East–West and North–South.
- Cooling system capacity: up to 150 kWt, depending on the operating conditions.
- Uncertainty of flowrate measurement: better than 1.0 %.
- Uncertainty of inlet/outlet water temperature: ±0.1 ºC to 0.525 ºC (0 ºC to 250 ºC)

4. New facility description

The design of this new test facility is defined both by the operating conditions to carry out the testing (Fernández–García, 2018), and by the restrictions included in the certification standards: ISO 9806:2017 and ASTM E905–87:2013. Because of that, the instrumentation chosen is the best of state of the art, for fulfilling the measurements uncertainty restrictions in the certification standards.

Two orientations for the collector field are possible: East–West for determining the optical and thermal performance in reduced test periods thanks to the possibility to have different incidence angles during the same testing day, and North–South for determining the thermal performance in commercial configuration. The facility has all the necessary elements: feed water system, heating system, cooling system, instrumentation and control system, auxiliaries, etc.

The balance of plant (BoP) is the installation around the solar collector with the capacity of feeding it with water at the fixed temperature, pressure and flowrate for testing, and with the cooling ability to dissipate the thermal energy generated in the solar collector in the air cooler before the water returns to the feed water tank. An auxiliary heating system is included as well for pre–conditioning the feeding water temperature to the solar collector system. In addition, both the design of the installation itself and the control system must be able of keeping the operating conditions in steady state.

The first important feature in this project is the used material, that is stainless steel AISI 304 or better in all parts in contact with the water, to avoid corrosion problems linked to the use of carbon steel.

The maximum operating temperature of 250 ºC corresponds to the collector outlet temperature. It is usually in this type of facility that the admissible maximum temperature in the rest of the installation is lower than the maximum temperature, but in this facility, the design temperature in overall part of the installation is 250 ºC, or even higher in almost all mechanical equipment.

This maximum temperature involves the maximum pressure required in the whole installation. Likewise, the maximum allowable working pressure of the installation is at least of 4.8 MPa (manometric). In order to fulfill the operating conditions, it was selected the Class 600 of the standard ASME B16.34 and ASME B16.5 instead of the standard DIN EN 1092–1, because of the rating PN63 does not fulfill for all of stainless steels, and the rating PN100 is well above for the requirements.

A simplified scheme of the BoP of this experimental testing facility is shown in the Figure 1.

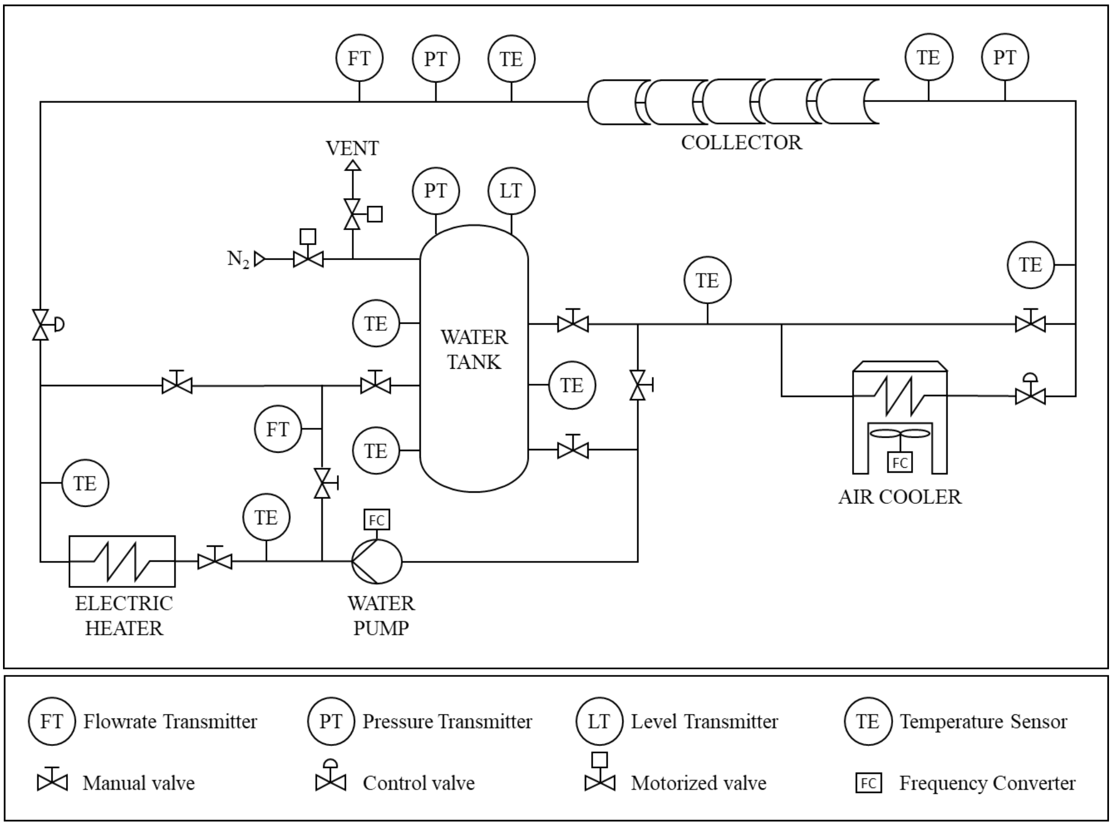

Fig.1: Simplified scheme of the new PSA's experimental facility for testing line–focus tracking solar collectors

4.1. General layout

The general layout of the test facility has enough field area around to install solar collectors in both directions (North–South and East–West) as shown in the layout of Figure 2.

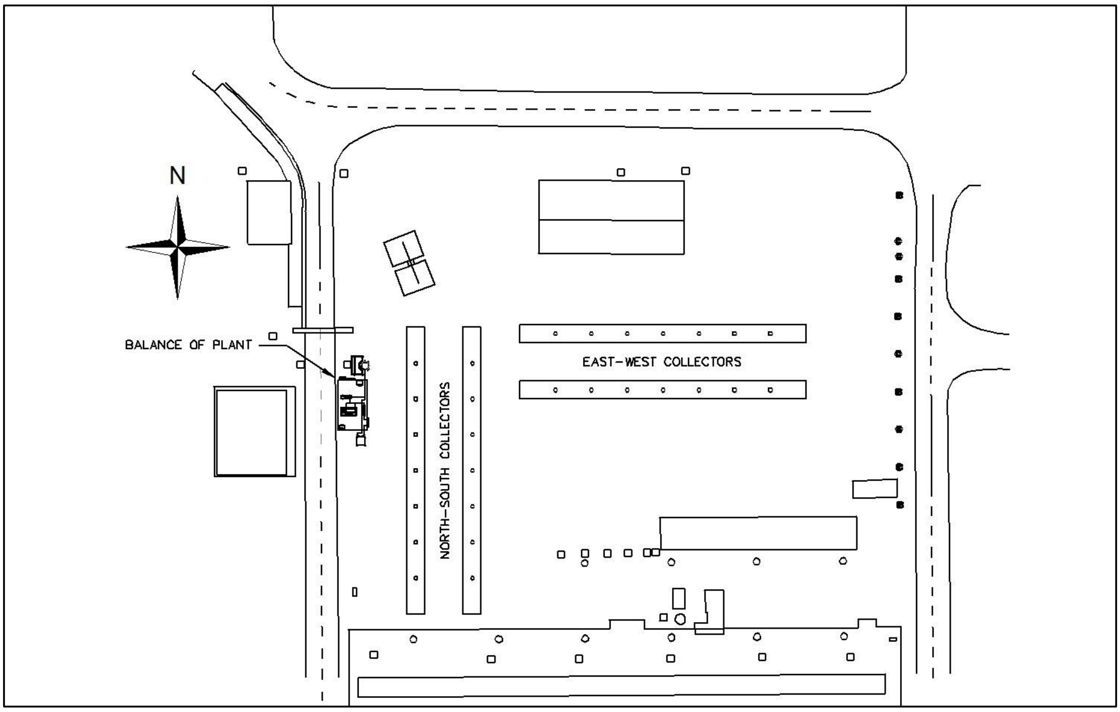

Fig.2: General layout of the new PSA's test facility

The location of the main equipment of the BoP is shown in the Figure 3. There is a reserve area for the future installation of an air condenser in the case of direct steam generation solar collector field will be tested.

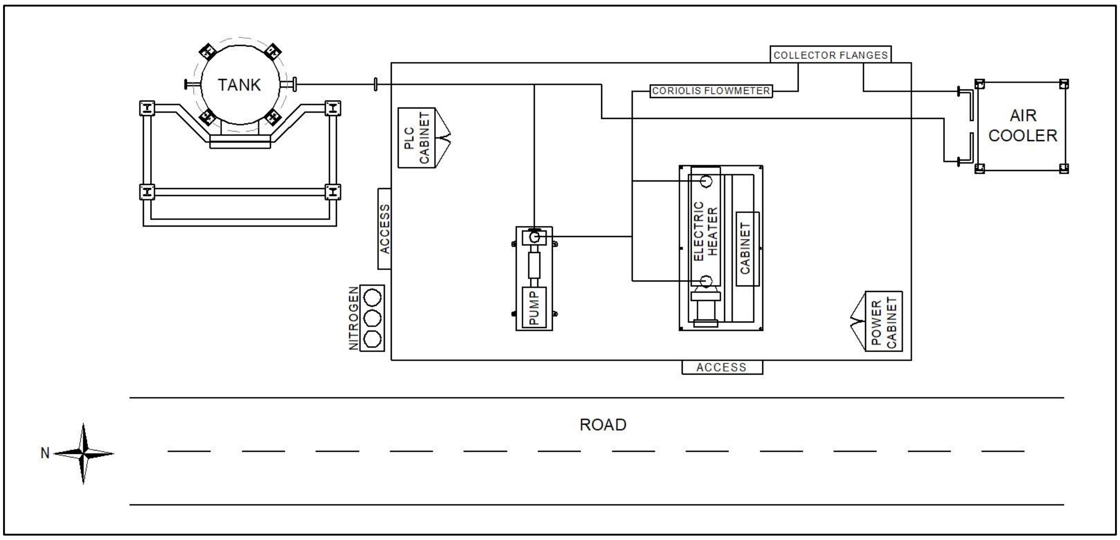

Fig.3: BoP layout with the main equipment

4.2 Water tank

The volume of the tank is 3000 l, which is enough to contain more than 2000 l of water, and so, with the capacity to maintain the feeding condition to the solar collector at least for one hour at the maximum flowrate of 1800 $l \cdot s^{-1}$. The tank is installed in vertical position, with a diameter around 1 m and a height of 3.5 m.

The tank has three inlet/outlet flanges, with one reserve flange, to configure it as needed. These flanges are bigger than corresponding pipe for allowing the insertion of different types of diffuser inside, so the tank could be configured as expansion tank, feed tank, or even with stratification of temperature to keep the outlet temperature nearly constant. With this target, the temperature is measured in three different levels. The nether outlet flange is lateral and not at the bottom, to avoid vortex formation and possible deposition of particles.

A nitrogen pressurization system is connected to the top, with two motorized on/off valves for feeding nitrogen and for venting, respectively. In this way, the overall installation keeps pressurized.

The maximum allowable working pressure (MAWP) of this component is 50 MPa at 280 ºC.

4.3 Water pump

Due to its tough working conditions a water pump with higher capacity than required has been chosen, because of that a recirculation pipe is needed. The pump is centrifugal and the coupling is magnetic. An additional cooling system is not required.

The water pump can work up to 280 ºC, with a maximum pressure in the discharge of 4.8 MPa.

4.4 Electric heater

The electric heater is installed in line (not in the water tank, like in the original installation CAPSOL). Although this situation of the electric heater complicates the installation, it provides more operation capacities for testing, and it can be operated in two different ways:

- fine regulation of the temperature, both in the inlet and the outlet of the solar collector, with the aim of compensating the small heat losses in the piping.
- preheat the overall water of the installation up to the temperature set point to start the testing.

A pressure switch, a level switch and a resistance temperature switch are installed to guarantee a safe operation. The MAWP of the electric heater is 50 MPa at 280 ºC.

The heating power is 24 kWt, that is regulated with thyristors in the overall range in the own electric cabinet. This power allows to preheat the installation and the 2000 l of water in 20 hours, from 25 to 225 ºC, and a thermal increase of 11.5 ºC with the maximum testing flowrate of 0.5 $kg \cdot s^{-1}$.

4.5 Air Cooler

The capacity of the air cooler was selected as a compromise solution, since the cooling capacity increases quickly with the inlet water temperature. Finally, the cooling power of the air cooler is from 50 kWt to 300 kWt with inlet water temperature of 75 ºC and 250 ºC respectively, taking in account an ambient temperature of 40 ºC.

The manifolds are assembled with flanges and pipes of a diameter of one inch, while the internal pipes have a diameter of half inch, with aluminum fins.

A frequency converter connected to the fan electric motor is used to regulate the outlet water temperature in the low temperature range, while in the upper temperature range is necessary a control valve in the bypass of the air cooler to limit the water flow to be cooled and limit the air cooler performance.

The MAWP of the air cooler is 50 MPa at 280 ºC.

4.6 Piping and valves

As mentioned above, the Class 600 of ASME was selected for valves and flanges. Some valves have higher Class for supply reasons. Different types of valves have been selected to be tested for this type of installation, and then, make the installation itself to have experimental characteristics.

The pipe was selected with Schedule 10S for pipe of one inch, and 40S for pipe of two inches; mainly for reasons of mechanical strength rather than hydrostatic pressure required.

The entire installation will be insulated with stone wool with thickness from 40 mm (piping) to 100 mm (water tank, electric heater).

4.7 Instrumentation and control system

The instrumentation complies with the requirements of the testing standards. The instruments involved directly in the collector performance measurements have the best accuracy available in the state of the art of the instrumentation manufacturers.

A Coriolis flowmeter has been selected, with an accuracy of 0.1% in full measuring range from 0.05 $kg \cdot s^{-1}$ to 0.5 $kg \cdot s^{-1}$; this instrument measures as well the volumetric flowrate, the pressure and the density.

For water inlet/outlet temperature measurements, resistance temperature detector (RTD) type Pt100 have been selected, with Class AA (IEC 60751), and 4–wire connection, that is the best state or the art. Even in this case, the accuracy is from ±0.1 ºC to 0.525 ºC, not enough to fulfill the standard ISO 9806. The PSA is working for improving the uncertainty in the differential temperature measurement through the collector for fulfilling the standard requirement.

For the rest of the installation thermocouples Type T with Class 1 have been selected (IEC 60584–1), with an accuracy from ±0.5 ºC to ±1.0 ºC depending on the measured temperature; and a vortex flowmeter for measuring the recirculation flowrate with an accuracy of ±0.75 %. All the pressure transmitters have a very high accuracy of ±0.0275 bar.

The ambient conditions (direct solar irradiance, ambient temperature, wind speed and direction) are measured with existing equipment from a neighbor test facility. Direct solar irradiance is measured with a pyrheliometer model CH1 by Kipp&Zonen (Valenzuela et al., 2014). The direct normal irradiance measurement has an average instrumental error of ±10 $W \cdot m^2$.

The main automatic control loops are the following:

- Inlet or outlet water temperature by regulation of the heating power in the electric heater.
- Flowrate through the solar collector by regulation with the frequency converter for speed regulation of the water pump, and with a control valve for fine regulation.

- Return water temperature to the tank by regulation with the frequency converter for speed regulation of the air cooler fan, and with a control valve of the bypass for the high range of temperature.
- Gas phase of nitrogen in the upper tank by actuation of both motorized valves of nitrogen and vent.

The control system has some safety interlocks for avoiding unsafe operations of the installation. A PLC cabinet will be installed on site in the installation, and the SCADA system will be installed at the control room. The power and PLC cabinets will be installed in opposite corners for avoiding electrical interferences between them (as shown in Figure 3).

The wiring will be conventional with 2–wire for 4–20 mA signal and power supply, with communication protocol HART. Others instruments have communication protocol MODBUS. As mentioned above, ATEX version is not required.

Although the instruments are calibrated on factory, all instruments can be re–calibrated in the own PSA's electronic laboratories.

Currently, the basic engineering of the project, P&ID, technical specifications and purchasing of the water pump, expansion tank, electric heater, air cooler, manual valves and instrumentation have been completed. And the following tasks are under execution: piping flexibility and temperature expansion studies with AutoPIPE, (as shown in Figure 4), erection specification and isometric drawings, foundation technical specification, and electrical and PLC cabinets specification.

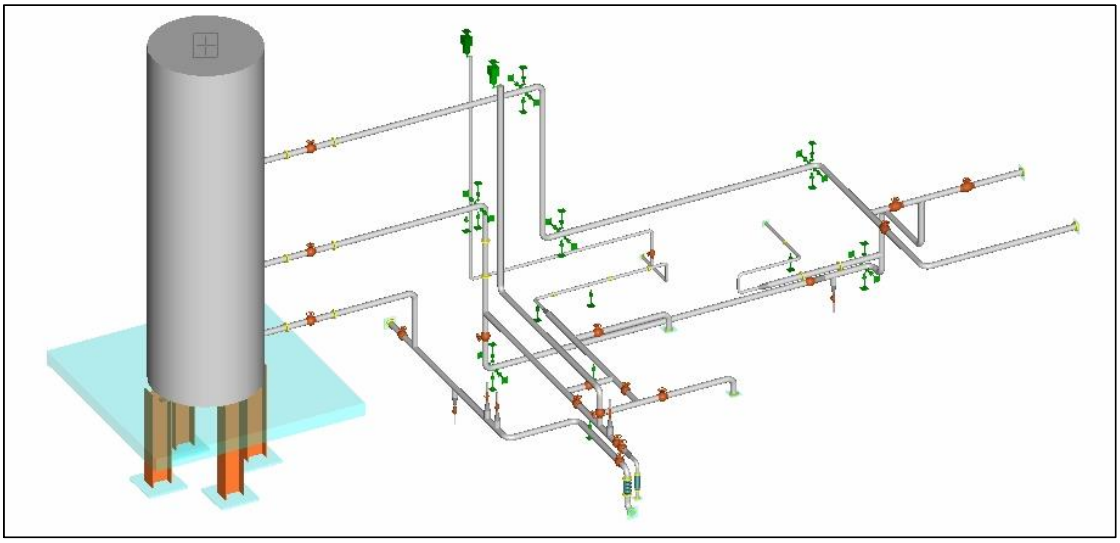

Fig.4: Exemplary scheme of flexibility and temperature expansion studies with AutoPIPE of the BoP of the new test facility

5. Operation modes and testing procedure

The operation modes of the installation are the following:

- Filling and emptying the installation with water.
- Pre–heating the installation.
- Cooling the installation.
- Feeding the solar collector for testing.

Since the collectors can be placed in both North–South and East–West orientation, two types of tests can be carried out on them:

- Optical and thermal performance testing of collector, in East–West orientation.
- Thermal performance of collector in commercial North–South orientation.

The new test facility also allows the testing of new BoP equipment (small thermal energy storage units, heat exchangers, micro–turbines, etc.) designed for SHIP applications. Since it is expected to have several collector units installed on site, solar thermal energy produced can be used to test new equipment for industrial heat applications.

6. Conclusions

This installation provides the PSA with a new test facility to carry out optical and thermal performance testing, in both testing and commercial collectors orientation, for a complete evaluation of any small–sized line–focus solar collector designed for solar heat in industrial processes, both from the point of view of testing and improving the manufacturers' designs, as well as for certification of the performance of the equipment that has reached the commercial distribution.

7. Acknowledgments

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