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Thermo-Mechanical Cycling of the ROTAJOINT Flexible Interconnection Installed in a Parabolic Trough Test Facility

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Abstract. Rotation and expansion performing assemblies (REPA) are one of the key components of parabolic-trough collectors (PTC) solar fields. This element is a flexible connector that connects the moving absorber tubes between adjacent PTCs or the absorber tubes to the fixed pipes of the solar field. A hybrid REPA model consisting of a flexible hose and a swivel joint, manufactured by the Spanish company ROTARM, has been installed in one of the PTC of a pilot plant at the Plataforma Solar de Almería (Spain) and tested to evaluate its life-time performance. Due to the lack of standardized procedure for testing this type of components for use in PTC solar fields, a test procedure has been defined consisting of a continuous thermo-mechanical cycling of the component to evaluate its performance under real conditions and to check any possible wear or failure. The total number of accumulated cycles has been 4000, which means that the tested REPA can withstand at least 10 years of trouble-free operation**,** if the periodic revisions and maintenance actions are carried out according to the manufacturer's specifications.

Keywords: Parabolic Troughs, Rotation and Expansion Performing Assemblies, Flexible Hose, Swivel Joint, Thermal Cycling, Mechanical Cycling, REPA

1. Introduction

In solar thermal power plants that use parabolic trough collectors to capture solar energy and convert it to heat and electricity, the pipes that distribute the heat transfer fluid (HTF) through the solar field are fixed, allowing only their thermal expansion, while the collectors are rotating elements that hold in their focal line a heat-collecting element (HCE), i.e. the absorber pipe through which the HTF circulates. Since the collectors move throughout the day following the Sun and the axis of rotation of a PTC is usually not aligned with its focal line, an interface between the moving HCE and the fixed pipe is necessary. In addition, temperature cycling up to 400 °C or more requires a linear compensation of the thermal expansion and contraction of the HCE. By using flexible pipe interconnections, the adaptation of the thermal expansion as well as the rotational movement of the HCE is ensured. Flexible hoses, swivel joints and ball joints are used to make the elements of the piping system flexible. A set of these flexible interconnections is called Rotation and Expansion Performing assembly (REPA) [1].

When Solar Energy Generating systems (SEGS) plants were built in United States, flexible hoses were used to make the connections. Later, in an attempt to reduce operation and maintenance problems associated with flex hoses, due to pressure drops in the original designs and occasional failures that were catastrophic because they resulted in HTF leakage, rotary ball joint type connections were designed and installed in the solar fields of these SEGS plants [2]. Since then, REPAs have been one of the key and critical components in PTC solar fields and, still today, new developments are being carried out to achieve higher reliability and lower investment costs, while offering parasitic power requirements.

With this objective, the Spanish company ROTARM, formed by the alliance of two companies specialized in valves and industrial solutions (Goizea S.L. and Arflu), is designing and manufacturing REPAs for PTCs. The company currently has two connector designs, the ROTAJOINT hybrid model and the ROTABALL model, composed of ball joints [3]. This paper presents the results of test performed with a prototype of the ROTAJOINT hybrid model, composed of a flexible hose and a swivel joint, which was installed and tested in one of the PTCs of the HTF test loop at the Plataforma Solar de Almería (PSA) (Spain).

On the other hand, one of the challenges of last years is the preparation of standardized test methods to qualify, under representative conditions, the different key components of solar thermal power plants, in particular for PTC solar fields [4]. In this context, several standards are already available, promoted by the Spanish standardization committee UNE/CTN 224 [5] or the international standardization committee IEC/TC 117 [6]. There are already published standards for solar mirrors, heat transfer fluid, solar receivers, etc. but not for REPA testing, although for the latter component there is already a draft Spanish standard ready for publication [7].

Few test rigs for accelerated ageing of REPAs have been developed in recent years. The Spanish CIEMAT and the German DLR developed a test bench at the Plataforma Solar de Almería that allows mechanical fatigue testing of REPAs at constant and elevated HTF temperature (up to 450 ºC) [1]. The Department of Engineering Physics of Wisconsin-Madison also has a test bench for prototype REPAs with molten salts [8]. But one of the limitations for existing test rigs for REPAs is that accelerated tests combining mechanical and thermal fatigue are not possible with their current configurations.

This paper presents a defined test procedure to perform a continuous thermo-mechanical cycling test of a prototype REPA, the ROTAJOINT solution, developed by the company ROTARM, installed in a full-size PTC of one of the pilot plants at the Plataforma Solar de Almería. The purpose of the test is to evaluate the performance of the REPA under representative operating conditions and check for possible wear or failures. The article is completed with a summary of the main results obtained during the test.

2. Methodology

This section presents the details of the tested REPA system, the experimental set-up and the defined test procedure.

2.1 Description of the experimental set-up

For the testing of the ROTAJOINT connection assembly (Figure 1), ROTARM manufactured and installed a unit of this system at the outlet of one of the PTCs, an UrssaTrough half-collector [9], of the HTF test loop at the PSA (Figure 2). This PTC installed at the PSA is oriented in east-west direction. As this is a half-collector, the drive unit is located in the inlet of the collector, to the east. For the design of the ROTAJOINT component, the dimensions of a standard PTC as installed in Spanish solar power plants were considered, which are also the dimensions of a standard UrssaTrough collector, i.e. aperture width equal to 5.76 m, collector length equal to 150 m, and absorber tube diameter of 70 mm.

The heat transfer fluid used in the circuit is a silicone-based oil from Dow Chemical, Syltherm® 800 [10]. This HTF can be used over an operating temperature range of 40 °C to

400 °C. The vapour pressure of this HTF at the maximum operating temperature (400 °C) is 13.73 bar. Its density and viscosity at room temperature (20 °C) are 935 kg/m^3 and 10.03 mPa·s, and at the maximum operating temperature (400 °C) are 547 kg/m^3 and 0.25 mPa·s, respectively. This is not a type of HTF currently used in solar power plants, but the operating conditions (temperature and pressure ranges) are quite similar to the eutectic mixture of biphenyl and diphenyl oxide typically used in commercial solar fields with PTCs. In PTC solar fields the HTF pressure is higher to the vapour pressure of the HTF at the maximum temperature, to avoid vaporization of the fluid in the system. In the solar field outlet, the pressure is typically between 15 and 17 barg and, in the collector loops, is between 16 and 18 barg.

During the tests, the control and acquisition of the process data (HTF temperature at the collector inlet and outlet, HTF flow rate, HTF pressure, direct solar irradiance (DNI), among other process variables) is managed by a supervisory control and data acquisition system (SCADA), which allows monitoring and controlling the operation of the entire test facility from one of the PSA's control rooms.

The REPA installed and tested consists of the following elements (Figure 1):

- One cylindrical swivel joint, 2.5-inch diameter, connected to the rotating axis of the collector by means of an adjustable telescopic element, which absorbs the expansion of the structure.
- Flexible hose connecting the end of the fixed pipe reel located at the outlet of the last receiver pipe (HCE) of the PTC and the swivel joint. This flexible hose is prepared to absorb the expansion of the HCE. It is made of stainless steel material.
- Kinematic joint support system, independent of existing structures, and thermal barriers, to prevent thermal propagation to structures.
- Flexible thermal insulation assembly of the integrated solution (not shown in Figure 1 but it can be seen in Figure 2).

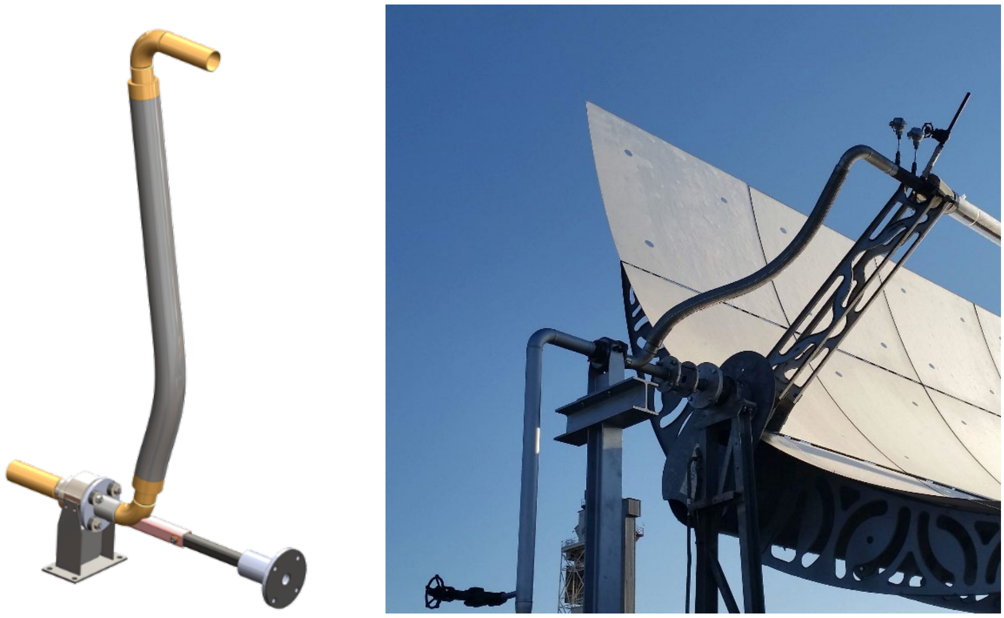


Figure 1. (left) Sketch of a 3D model of the ROTAJOINT design [3] and (right) view of the ROTAJOINT solution manufactured by ROTARM and tested at the Plataforma Solar de Almería.

Figure 2. View from the west of the UrssaTrough parabolic trough at the Plataforma Solar de Almería (east-west orientation), with a ROTAJOINT connector installed at the collector outlet. (Note: Fluid flow direction to the camera).

The experimental set-up is completed with temperature sensors, thermo-resistances type PT-100, installed in thermowell, which allow to measure the temperature of the HTF at the outlet of the collector (and therefore at the inlet of the REPA). These sensors are installed in the fixed pipe reel located at the outlet of the last HCE of the PTC.

The assembly that makes up the tested REPA allows the absorption of the displacements of the receiver pipe in the different positions of rotation of the collector, since it rotates solidly and always works in the same plane.

2.2 Test procedure

To simulate the performance of the ROTAJOINT solution under real-life conditions, the following test procedure includes three types of cycling patterns to reproduce different scenarios of operating conditions that affect the performance of REPAs and typically occur during the operation of commercial solar fields, and that produce heating/cooling and simultaneously a mechanical displacement/rotation of the REPAs.

The first type of cycling defined is related to a defocusing of the collector due to HTF overheating or any other alarm related to this automatic safety action of the control system. This defocusing involves a rotation of the collector some degrees from its sun-tracking position, which guarantees the HCE is not collecting concentrated solar radiation and causes a decrease in the HTF temperature. In existing commercial power plants, the configuration of PTC loops in the solar field is such that the HTF temperature rise is about 25 ºC per 150 m long collector, under nominal operating conditions. In the defined test, when this type of cycling, which has been termed “short cycling”, is executed two rotation steps are performed. During the whole test the HTF mass flow rate is maintained constant. The first step is a 10-degree rotation from the sun-tracking position to a defocus position, which causes the HTF temperature to decrease by 40 to 50 ºC, a more demanding requirement in these accelerated REPA performance tests. In the second step, the rotation is again 10 degrees back from the defocus position to the sun-tracking position, which causes the HTF temperature to increase again by 40 to 50 ºC.

The second type of cycle defined in the test reproduces a large rotation of the collector from the sun-tracking position to a new defocus position, with about 90-degree rotation instead of the previous 10-degree rotation, with a heating/cooling of the HTF of about 100 ºC, which is the actual temperature change between the inlet and outlet of the PTC loops in commercial solar fields working with biphenyl/diphenyl oxide as heat transfer fluid (from 293 ºC to 393 ºC). This type of cycle is called „intermediate cycle“. Again, this cycle involves simultaneous mechanical and thermal cycling of the REPA.

Finally, to reproduce a collector rotation greater than 120 degrees with increased cooling of the HTF, which can occur at the evening when the PTCs move to the stow position (if this is defined as eastward in north-south PTC solar fields located in the northern hemisphere), the third type of cycle defined is called „long cycle“ and is composed of a single step rotation. This movement is ordered when there is no solar radiation available to continue the heating of the HTF with solar energy and collectors are positioned to their safe stop position.

With this definition of types of cycles, the test was implemented to verify the long-term operation of the ROTAJOINT prototype installed in a PTC of the HTF test loop at the PSA. Table 1 summarizes the main characteristics of the test, and shows the percentage weight of each cycle type in the overall test. In addition, Figure 3 shows a simplified schematic of the HTF temperature changes that occur in the different cycles that make up the singular test.

Table 1. Main data of the singular test procedure defined for the testing of the ROTAJOINT solution installed in a parabolic-trough collector at the Plataforma Solar de Almería.

Parameter	**Short cycles**	**Intermediate cycles**	**Long cycles**
Angle of rotation	~10 degrees	~90 degrees	>120 degrees (rotation to stow position)
HTF temperature change from the nominal value	~50 ºC	~100 ºC	>300 ºC (from $T_{HTF, hot}$ to $T_{HTF, cold3}$)
Inlet HTF temperature	1st step: ~390ºC ($T_{HTF, hot}$) 2nd step: ~340ºC ($T_{HTF, cold1}$)	1st step: ~390ºC ($T_{HTF, hot}$) 2nd step: ~290ºC ($T_{HTF, cold2}$)	~390ºC (only one rotation step)
Cycle duration (min)	12 to 14 min	30 min	30 min
Percentage of cycles in the whole test	~85 %	~5/10 %	~5/10 %

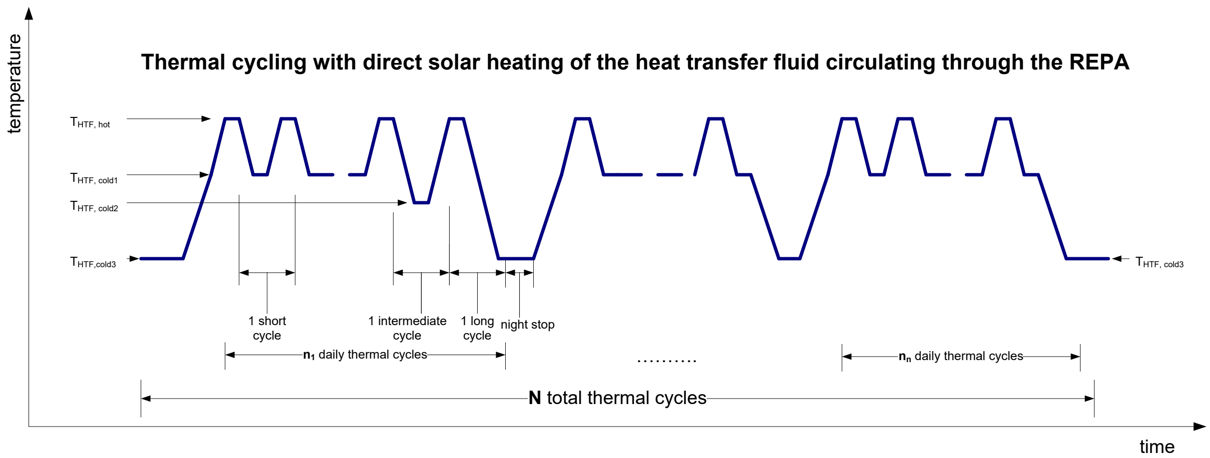


Figure 3. Simplified sketch of the thermal cycling of a REPA installed in a PTC.

3. Results

The testing of the ROTAJOINT solution in the HTF test loop was completed in May 2021, after 1300 hours of accelerated testing since June 2020, under nominal operating conditions, and more than 4000 cycles performed on the ROTAJOINT prototype. Table 2 presents a summary of the number of cycles of each type performed throughout the test. This number of cycles performed are within the range initially agreed with the manufacturer before the start of the test campaign (see Table 1).

Table 2. Breakdown of the accumulated cycles of the ROTAJOINT solution installed in the HTF test loop at Plataforma Solar de Almería.

Short cycles	Intermediate cycles	Long cycles	Total number of cycles
3542 (88%)	151 (4%)	310 (8%)	4003 (100%)

Figure 4 shows representative graphs of a typical test day. As can be seen, the average number of thermo-mechanical cycles achieved during a test day (i.e. the standard working time of the test facility staff) is 25 to 30. A constant volumetric flow rate of about 15 m^3/h is circulated through the system, and when the nominal operating conditions are reached, the collector is moved from the sun-tracking position to the defocus position, which causes the REPA to rotate (the angle depends on the type of cycle), and simultaneous cooling or heating of the heat transfer fluid inside the REPA occurs. Figure 5 shows two different views of the system during a short cycle on one of the test days: (i) with the collector tracking the sun with no defocusing angle, which means that the HTF is heated with concentrated solar energy at the maximum temperature ($T_{HTF,hot}$); and (ii) with the collector tracking the sun with a defocusing angle, which means that there is no concentrated solar radiation incident on the HCE and, therefore, the HTF temperature drops by about 40 to 50 °C, to $T_{HTF,cold1}$, during the 2nd step of the short cycle.

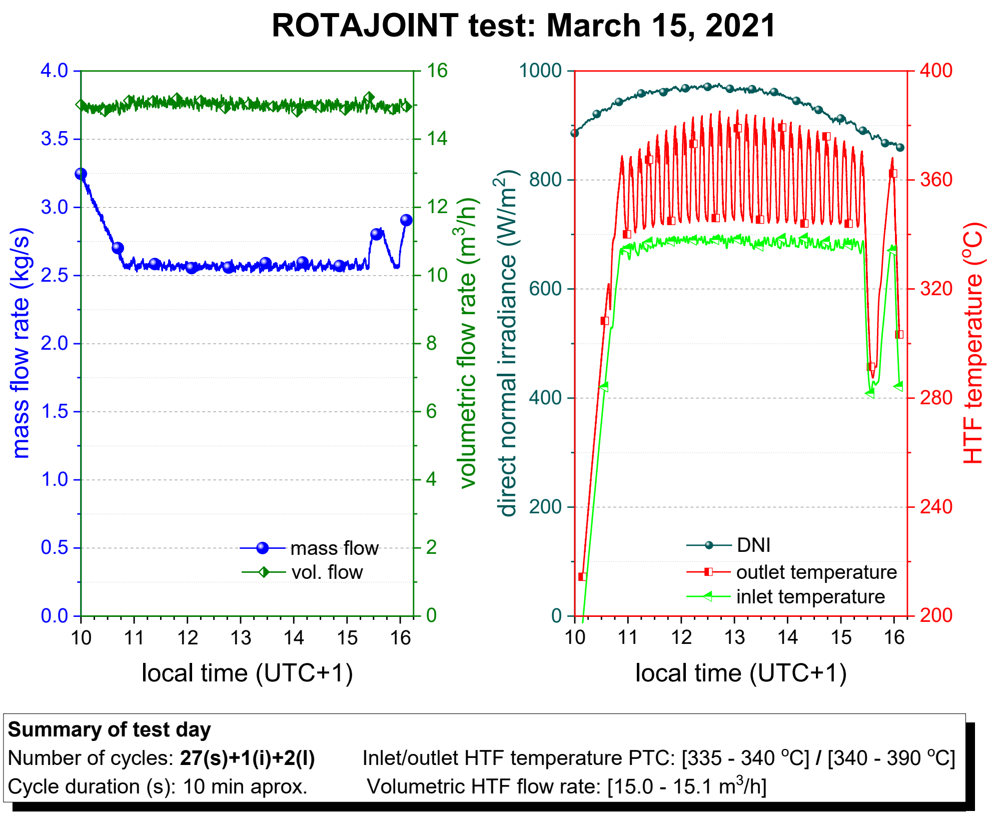
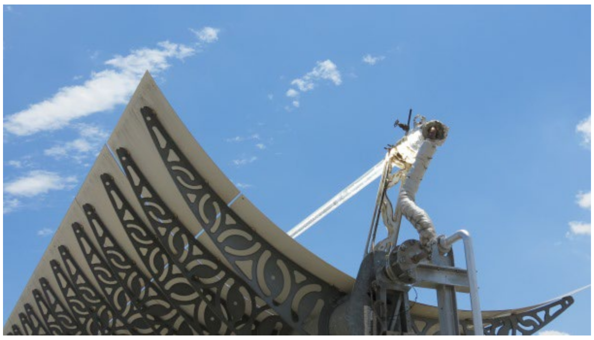


Figure 4. Graphs showing relevant process parameters during a typical test day: (right) HTF mass and volumetric flow rates (in kg/s and m^3/h, respectively), and (left) direct normal irradiance (in W/m^2), and HTF inlet/outlet temperature (in °C).



(a)

(b)

Figure 5. View of the collector with the REPA installed at the outlet during a short cycle: (a) tracking the sun without any defocus angle and (b) tracking the sun with a defocus angle.

4. Discussion

The experimental set-up and test conditions defined and performed allow for accelerated testing of REPAs in a full-scale test facility with installation and operating conditions that are representative, in terms of HTF temperature and pressure, of system operation in commercial solar power plants. Given the current lack of a standardized procedure for qualifying this type of component for solar thermal power plants, this approach is considered a valid option for testing the performance of REPAs for manufacturers developing this type of mechanical solution for commercial systems.

Considering the following correlation between the cycles performed in the accelerated test and the service life of a REPA when installed in the solar field of a commercial solar thermal power plant:1000 cycles would correspond to approximately 2.5 years of operation, it can be concluded from the test performed that the tested ROTAJOINT unit can withstand at least 10 years of trouble-free operation, if the periodic checks and retightening of the swivel joint are performed according to the manufacturer specifications.

Currently, the tested ROTAJOINT prototype is still installed in the PTC of the HTF test loop, but operating under standard conditions, i.e., without subjecting the joint to an accelerated cycling test.

The test procedure presented in this article can be adapted to the system requirements and operating conditions of any commercial system by changing the percentage of cycles of each type and/or temperature/angle of rotation, and by increasing or decreasing the total number of cycles performed.

As an improvement to this test procedure, forces and torques during cycling will be monitored in the future to complete the information describing any degradation process of the REPA during its lifetime [11].

Author contributions

Conceptualization, L.V., J.H., J.G.; Resources: L.V., J.G., J.H., J.A., G.M.; Methodology, L.V., R.L.M.; Data curation, L.V., R.L.M.; Validation, L.V., R.L.M.; Writing – original draft, L.V.; Writing – review & editing, R.L.M., G.M.

Competing interests

The authors declare no competing interests.

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