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EuroDish Solar Receiver Thermo-Mechanical Failure Detection Assessment and Improvement Opportunities

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Abstract. In Dish Stirling systems, the solar receiver design is a key factor. Being this a critical element the objective of this work is to analyze a real solar receiver. The aim is to know where a solar receiver fails. The method used in this work can be applied to different solar receivers. The solar receiver selected for the analysis is the one in the Eurodish system. In order to accomplish the objectives a thermo-mechanical simulation of this solar receiver has been performed. Experimental data from two different installations and two main software programs have been used in this simulation process. The simulation shows how the receiver is deformed by the heat flux coming from the sun. In this particular receiver geometry, the critical point is located in the junction area between the bottom tubes and the manifold. The results show a clear coincidence with experimental experience, validating the simulation.

Keywords: Dish-Stirling; EuroDish; Thermal simulation; Fatigue analysis; CSP

1. Introduction

Probably, the most promising renewable energy is the solar energy since it has a huge potential. There are three systems based on the concentration of the rays coming from the sun. These are central receiver, parabolic through and dish Stirling systems. Central receiver and parabolic through systems are appropriated for big scale production of electricity (up to 200 MWe). On the other hand, dish Stirling units have a maximum nominal power of about 25 kWe. However, this technology presents the advantage of modularity, with applications varying from isolated facilities for distributed energy to big facilities with the aggregation of a high number of units. Both central receiver and parabolic through systems have reached the commercial exploitation phase and have been installed in different locations around the world (especially parabolic through systems [1]). However, dish Stirling technology has not achieved the same level of development due to the lack of reliability in its performance [2]. One of the elements that present more problems in a dish Stirling is the solar receiver, since it has to support extreme conditions in its operation [3]. Being this a critical element in the performance of the whole system, the objective of this work is to analyze a real solar receiver. The solar receiver selected for the analysis is the one in the Eurodish system [4]. In this work a thermo-mechanical simulation of the receiver is performed, the critical zones of the receiver are identified and alternative solutions are proposed in order to improve the performance of the component.

2. The Eurodish Solar Receiver

In 1989, Schlaich Bergermann und Partner (SBP) and Stirling Power Systems (SPS) started a cooperation project to use the Stirling engine SOLO V160 in solar applications. As a consequence of this collaboration the dish Stirling Distal I was constructed. In 1997 the Distal II was created, improving the design of the Distal I. A new Stirling engine was used, the SOLO V161 [5]. The last stage in the evolution of

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this system was the development of the Eurodish system in which the main advance was the concentrator design. Supported by two different projects of the European Comission and the German environmental ministry (Eurodish project, 1998-2011. Envirodish project, 2002-2005), the main objective was to decrease the operation, installation and fabrication costs [6]. Several Eurodish units were installed in different referent locations as Odeillo (France) [7], the University of Seville (Escuela Superior de Ingenieros de Sevilla, ESI, Spain) [8, 9] the PSA and the Vellore Institute of Tecnollogy VIT (Italy) [10]. All these systems were analyzed to evaluate the improvement possibilities of the different elements of the system [11].

The solar receiver of the Eurodish system is a directly illuminated receiver (Figure 1). It is located inside a cylindrical ceramic cavity of 30cm in diameter and it is separated 12 cm from the cavity aperture. The receiver has 78 tubes made of Inconel 625 forming a hexagonal geometry. The tubes are 3 mm outer diameter and 1.8 mm inner diameter [7]. Behind these tubes 20 thermocouples are located in order to control the operation temperatures. The receiver must withstand very high temperatures (up to 950 ºC in the external surface). These temperatures induce stress and deformation in the receiver material in such a way that it is possible to lead to a failure of this element. Furthermore, the pressure inside the receiver can reach up to 140 bar, increasing the stress in the material. This is why an accurate and well planned thermo-mechanical analysis is essential.

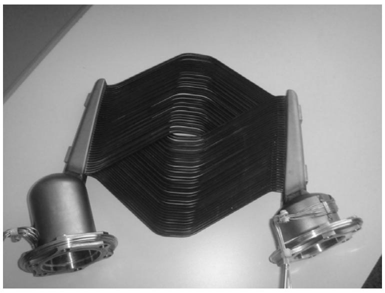

Fig. 1: Eurodish solar receiver

3. Methodology

The first step in this work is to calculate the temperature distribution in different tube sections of the solar receiver. Starting from twenty temperatures points and the solar irradiation in the receiver, the temperature distribution in twenty sections of the receiver is calculated. This is explained in section 4.1. The second step is to calculate the temperature distribution in a higher number of points. This is carried out using interpolating methods and dividing the receiver in different temperature zones.

Once the full temperature distribution has been calculated, the next step will be to calculate the static stresses and strains in the receiver. Temperature and pressure are the data input for the simulations that calculate these stresses and strains. The last step will be to perform a fatigue analysis in order to find the point in which the receiver first breaks.

Different data have been used to perform these simulations. The values introduced in the simulations have been those registered by the Eurodish control system during its operation. The two installations considered are the ones located in Odeillo and Seville. The selected data correspond to temperature and pressure registered in the Seville installation and the irradiation map elaborated from the data collected in the Eurodish system installed in Odeillo has been used [7].

4. Solar Receiver Simulation

In the thermo-mechanical simulation it is necessary to have pressure and temperature data in as many points as possible. Regarding the pressure this fact is not a problem, because the pressure is always uniform at the receiver and then, all the points have the same pressure at the same moment. However, the temperature data is limited to the receiver points in which a thermocouple is located. Therefore, a way to estimate the temperature in more points must be found. The solution is to perform a first thermal simulation in which a theoretical temperature distribution is obtained.

4.1. First Thermal Simulation

ANSYS software is used to carry out a thermal simulation that gives as a result a temperature distribution in a cross section of a generic tube in the solar receiver. A 3 mm outer diameter and 1.8 inner diameter tube is taken as the simulated geometry. The working fluid (Hydrogen) temperature inside the receiver is considered constant and uniform, and it is set at 650 ºC (ESI installation). The convection heat transfer coefficient is established in 6000 W/m2 [8]. The upper side tube is the zone where the concentrated solar irradiation arrives and the bottom is ideally insulated (the non-irradiated surface is resting above an isolating material). The input data are the temperature at the bottom of the section (registered with a thermocouple) and the solar irradiation at the upper face of this section (Figure 2). These data are taken from the Seville and Odeillo registers, respectively.

The obtained result in the simulation is shown in Figure 3. In this figure, the temperature distribution in a tube cross section can be seen. The lowest temperature is reached at the bottom part and the highest temperature is reached at the top. This process is repeated for each one of the sections in which there is a thermocouple. In this way the temperature distribution in twenty different sections of the receiver is obtained.

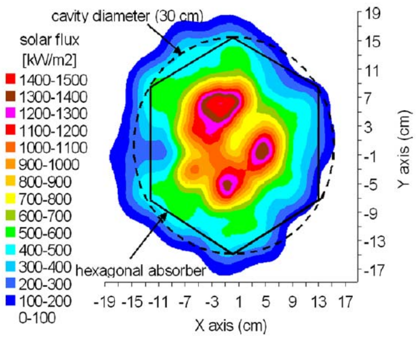

Fig.2:olar flux distribution [7].

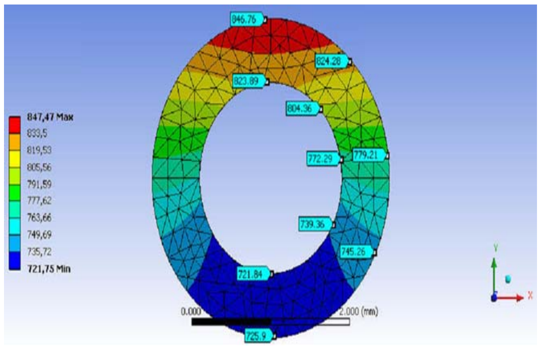

Fig.3:Temperature distribution tube (ºC).

4.2. Boundary Conditions

In the previous section, the method developed to calculate the temperature distribution in twenty sections has been explained. However, in order to have a complete characterization of the receiver loads, the temperature distribution in more sections is needed. So a new approximation is carried out where an interpolation of the thermocouples temperature values is performed. The objective is to obtain a theoretical temperatures map at the receiver bottom side (Figure 4).

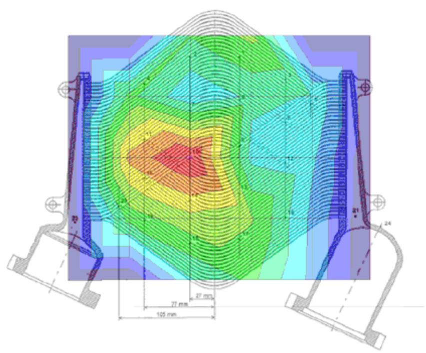

Fig.4: Theoretical temperatures map at the receiver bottom side.

5. Solar Receiver Thermo-Mechanical Simulation

The thermo-mechanical simulation carried out in this work has been performed using FEM software (Abaqus and I-DEAS). The study is a static analysis of the two stationary thermo-mechanical states. These two states correspond to the two extreme conditions (minimum and maximum requirement scenarios). In order to define the boundary conditions, the pressure and temperatures are introduced in the model in the way that has been explained in the methodology. The tubes material is Inconel 625 and the manifolds material is Multimet. First, the static stresses and strains, minimum and maximum, will be calculated. After this first result, the load cycles will be simulated too. For this purpose a fatigue analysis will be performed. In this analysis, the cycles in which the clouds appear and disappear will be simulated.

5.1. Fatigue Analysis

The thermo-mechanical breaks are caused by the strains generated by a combination of thermal and mechanical charges where both the stress and the temperature are time dependent. These types of charges are usually more dangerous than the isothermal fatigue at maximum temperature.

The life cycles number estimation is performed using a low-cycling thermo-mechanical fatigue prediction methodology (Mason-Halford Universal-Slope Method [12]) at the worst temperature and stress conditions. The operation cycle is defined by the two operation solicitations; maximum (thermo-mechanical state, 140 bar) and minimum (thermo-mechanical state, 20 bar) loads.

6. Results

The results showed that the maximum stresses reached in the receiver central area and in the joint between the tubes and the manifolds. The maximum stress is reached in a central point because the highest temperature is in this area. The global highest value is 543 MPa, while the highest value in the joint zone is 526 MPa. It was detected that the main contribution to the generated stresses has a thermal origin. The high pressure (140 bar) is not critical in the receiver operation. In this way, the tubes thickness is oversized respect of the pressure. Therefore the temperature is the more important agent affecting the studied system.

Looking at the FEM simulation results three critical points are detected. In these points a break could appear. These three points are (Figure 5): A (highest strain), B (global highest stress), and C (highest stress in the tubes-manifold joint zone).

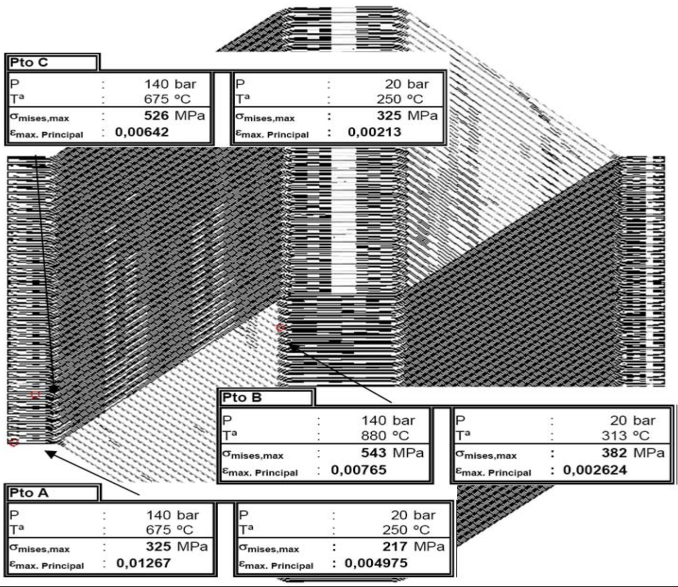

Fig.5:Critical points detected in the solar receiver.

The fatigue analysis results showed that, point A is the most critical point. The number of cycles in which the cracks may appear is between 6000 and 9000. This zone is the most dangerous because the temperature distribution is non-symmetric and the hot focus is slightly deviated towards the receiver left area. Therefore, the thermal gradient is higher in this zone. The different relative rigidity between the manifold and the first tube contributes to the appearing of concentrated deformations, being the possible cause of the life reduction in this point. The fatigue simulation results show how the weakest point is located in the left bottom part of the receiver. In the Eurodish installed in Odeillo, there was experiences in which the breaks where produced exactly in this area.

6.1. Improvement suggestions

Once we have seen the point in which the receiver breaks, three different solutions are proposed:

- One possibility is to make the distance between the dome and the first receiver tube bigger. By doing this, the manifold behavior is less rigid and the deformations amplitude in the first tube is reduced.
- The second option is to reduce the manifold thickness without varying the location of tubes and manifold. Making a thinner wall manifold, the flexibility will be higher and the difference between this and the one in the tubes will be smaller.
- The last option is to make the first tube stiffer in the critical zone. This could be achieved placing a shell around the tube in the junction area between tube and manifold. In this way a transition between a rigid area and a flexible area is created.

7. Conclusions

The thermo-mechanical performance of the Eurodish solar receiver has been analyzed and the critical points in this element have been identified. Data from two different Eurodish locations have been used. Once the simulation results have been analyzed it can be conclude that the methodology used is accurate enough to characterize the solar receiver performance since the results coincide with the real experience.

- The critical zone in this solar receiver is the one in which the lower tubes and the manifolds are joined. The fact that the simulation results match with the real experience in the Eurodish installations can be considered as a validation of the simulation.
- It is observed that the solar spot has a big influence in the stresses that this piece has to withstand. In order to achieve a good receiver performance, it would be necessary to have a more homogenous solar distribution in the receiver surface. This can be done optimizing the concentrator geometry and improving the solar tracking system.
- To solve the different relative rigidity between manifolds and tubes it is recommended to reinforce the lower tubes using a shell or to augment the distance between the first tube and the manifold base.

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