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Direct steam generation in parabolic trough collectors

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Abstract

Existing commercial parabolic trough power plants use thermal oil as a heat transfer fluid, with working temperatures in the region of 400ºC. In order to achieve more efficient generating systems, a second generation of parabolic troughs that operate at temperatures higher than 400ºC is being developed.
One possibility, Abengoa Solar is assessing, it is the use of direct steam generation (DSG) inside parabolic troughs in order to achieve higher temperatures; the first stage heating up to 450 ºC and the second stage heating up to 550 ºC. There is, however, a certain degree of complexity in the use of DSG technology that has resulted in it not yet being utilized in commercial plant designs. Due to the presence of saturated steam inside the parallel loops the required control system is more complex, particularly during transitory periods of radiation. Also the higher operating pressures and temperatures in the solar field mean that the receiver tubes and interconnections between collectors are very critical components. For this reason, typical systems utilize an intermediate fluid for energy transfer.
In order to overcome these challenges, Abengoa Solar has built a demonstration plant of 8 MWht. The plant is composed of an evaporator field with three parallel loops and a superheater field with two loops in order to work at 85 bar and 450ºC. The demonstration plant has been operated and evaluated for one year.
During this test period, the following have been evaluated and validated:

- An innovative control strategy system that guarantees the stability of the plant even under transient conditions.
- Receiver tube design able to achieve 450ºC, analyzing the mechanical behavior, optical performance, and heat losses.
- Different configurations of interconnections between collectors with ball joints and flexible rotation joints.

A theoretical model has been developed for commercial scale DSG plants and validated with experimental data obtained from the demonstration plant.

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1. Introduction

Existing commercial parabolic trough power plants use thermal oil as a heat transfer fluid, with working temperatures limited to 400ºC. A second generation of parabolic troughs that can operate at working temperatures higher than 400ºC has been designed and tested with the goal of improving system efficiency. Abengoa Solar is assessing, along with other fluid options, the use of direct steam generation (DSG) inside parabolic troughs, to achieve a higher operating temperature of around 550 ºC.

The complexity involved in the use of DSG technology has resulted in an intermediate fluid for energy transfer being utilize in existing commercial plant designs. The presence of saturated steam inside the parallel loops requires a more complex control system, particularly during transitory periods of radiation in order to maintain the desired operation characteristics. Also the higher operating pressures and temperatures in the solar field mean that the receiver tubes and interconnections between collectors are very critical components and need to be designed carefully for the new operation limits.

In order to overcome the challenges associated with DSG technology, Abengoa Solar has built, operated, and evaluated a demonstration plant of 8 MWht.

The prototype was operated for one year at 450ºC during which the control strategy and solar components were validated. After that year, new receiver tubes and interconnection between collectors were installed and have been tested for three months at 550C.

This paper summarizes the conclusions obtained after the evaluation period.

2. Prototype description and operation.

The prototype is located in Sanlucar la Mayor Solar Platform, in Seville (Spain) and produces around 8 MWth of thermal power. A simplified scheme of the facility is represented in Figure 1.

The plant is composed of three main systems; the evaporator solar field (EVAP) with three parallel loops of 800 meters each, the superheater solar field (SH) with two parallel loops of 200 meters each and the balance of the plant system (BOP) composed of a laminar valve and an air-cooled condenser.

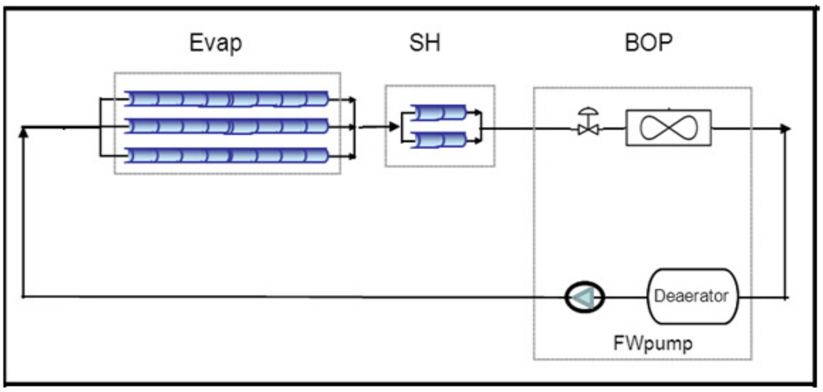

Fig.1 Scheme of the facility

The feed water enters the EVAP to be preheated and evaporated, producing saturated steam with a target percentage of steam quality. The bi-phased mixture is separated, the liquid water is recirculated and the dry steam enters the SH to produce superheated steam up to 450ºC at nominal pressure. In the BOP, a valve and air-cooler is used to reduce the pressure and condensate the steam. The loop is closed with the deaerator and the main feed water pump.

The demonstration plant has been operated and evaluated for one year producing superheated steam at 450ºC.

During this test period, the following have been evaluated and validated:

- An innovative control strategy system that guarantees the stability of the plant even under transient conditions.
- Current receiver tube designs able to operate at 450ºC; analyzing the mechanical behavior, optical performance, and heat losses.
- Different configurations of interconnections between collectors with ball joints and flexible rotation joints.

3. Evaluation results.

*3.1. Evaluation of the control stability***.**

A new control strategy has been designed to maintain stable production of superheated steam even under transient conditions. This strategy is designed to guarantee three different requirements:

- Minimum mass flow within the receiver tubes installed in the evaporator and superheater solar field.
- Stability of the evaporator solar field. By measuring operational parameters the system can detect possible changes in the radiation and react faster.
- Minimum superheating degrees. The conventional turbines require a minimum of 50ºC of superheating. The control strategy has been defined to guarantee this minimum superheating even under transient conditions.

The stability of the plant has been experimentally validated during operation for more than one year, assessing clear days, days with short-time and long-time transients in the radiation. Figure 2 shows the operation for each kind of day, the red line is the superheater temperature at solar field outlet and the darker blue line is the steam mass flow produced. The radiation (DNI) is represented by the dashed line.

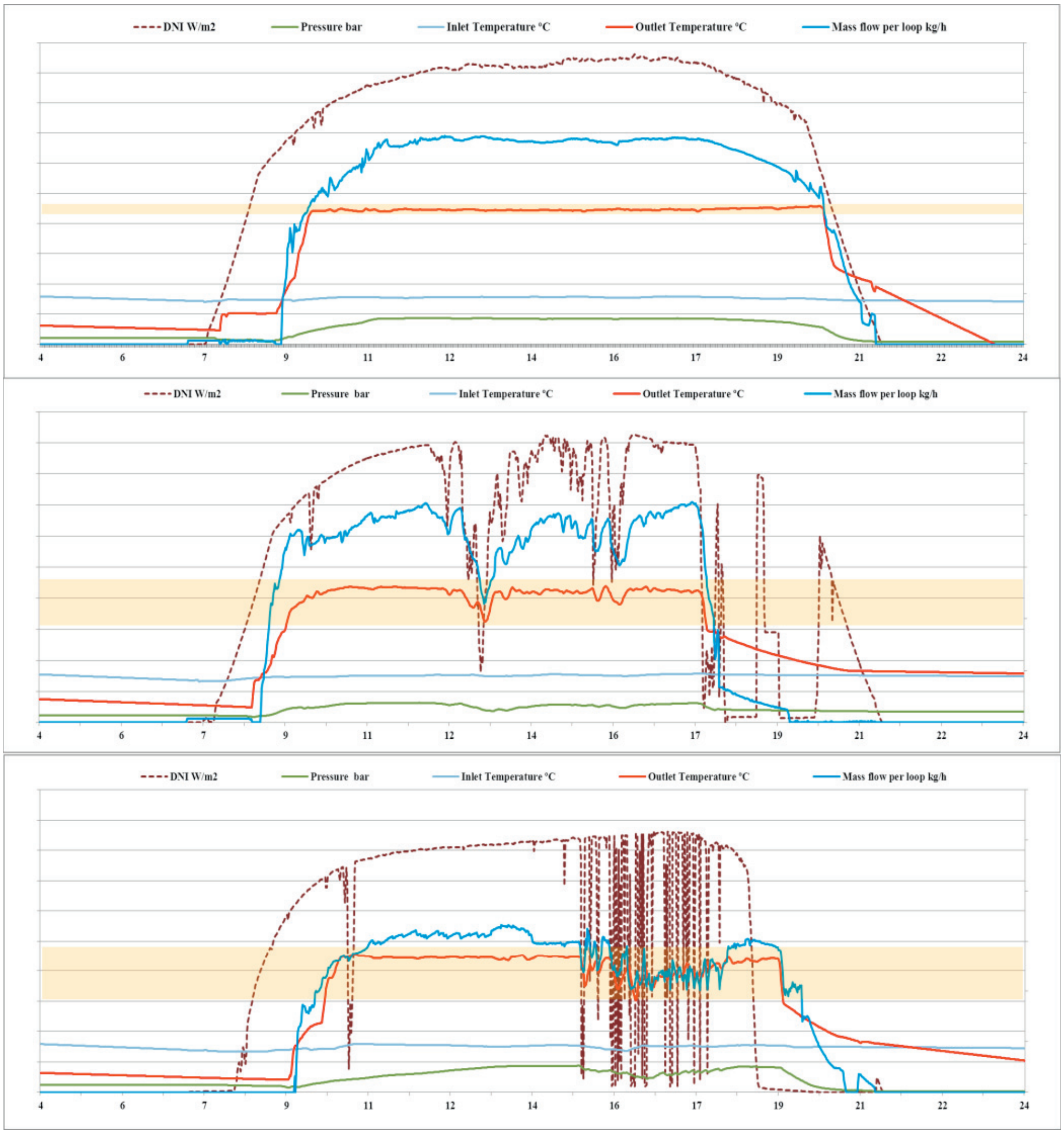

Fig.2. Control stability for different kinds of days;
(a) clear day, (b) day with long-time transients and (c) day with shot-time transients.

3.2. Evaluation of the theoretical model.

A theoretical performance model has been developed by Abengoa Solar in order to design DSG commercial plants. The reliability of this model has been validated with experimental results obtained from the demonstration plant.

The performance model is designed to take into account the total production in the entire day, including the different operation phases; start up, nominal operation, and shut down:

- Phase 1: Start up to achieve allowable conditions at turbine inlet. This phase requires special attention in the modeling to account for how the whole solar field should preheated.
- Phase 2. Operation under nominal conditions: Without transients in the DNI, the system produces steam at nominal conditions during the entire day.
- Phase 3. Shut-down of the plant: At the end of the day, the DNI will start to decrease and the nominal conditions are lost as consequences of decreasing of the irradiation.

The input data taken into account for the comparison of the results from the theoretical model and the experimental results are: direct normal irradiation (DNI) in W/m^2, characteristics of the collector and receiver tubes from supplier, estimations of cleanliness factors from reflectivity and transmissivity measures of mirrors and receiver tubes, respectively, and experimental measurements of temperature for the estimation of the thermal losses.

Figure 3 shows the comparison between theoretical and experimental data. The blue line is the theoretical data and the red line is the experimental data, with the deviation in the order of 5%.

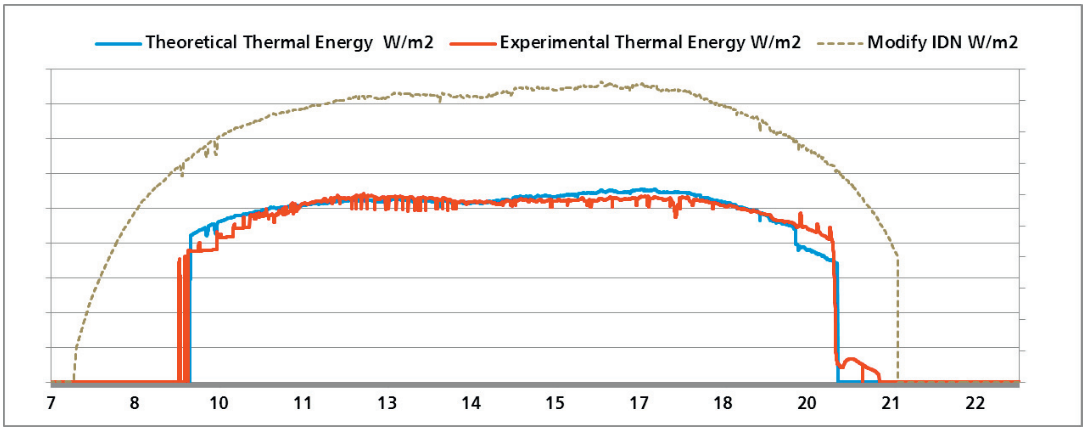

Fig.3 Comparison between theoretical and experimental results

3.3. Solar field components.

For DSG the combined weight of the receiver tube and the HTF is not a significant increase from the combined weight of the receiver tube and oil from a plant using oil as the HTF. Since there is no significant increase in the combined weight there is no need to redesign the parabolic collector and it is possible to assume the same parabolic trough collector design for DSG and oil.

Therefore, in comparison to the current plant designs using oil, DSG requires experimental validation of the new receiver tube and interconnections between the collectors due to the increase in design operating pressure and temperature. No new experimental validation on the rest of the collector is required.

With regards to the interconnections between collectors, different systems have been evaluated during the operation time:

- One configuration based on 2 ball joints.
- Two different configurations based on 3 ball joints.
- One innovation system based on flexible hoses with rotation joint.

There are two problems associated with the receiver tubes in a DSG plant: the possibility of a stratified vapor and liquid flow which deteriorates the inner wall cooling distribution in the evaporator field and poor inner wall cooling in superheater field. The direct consequence of this poor cooling is uneven radial temperature distribution which can cause buckling of the receiver tube with the possibility of the receiver tube breaking or being permanently deformed.

Both problems were analyzed in detail by Ciemat [1] and they have set minimum mass flow rate limits to ensure mass flow is high enough to ensure sufficient inner wall cooling and radial temperature distribution.

After 12 months of operation and operating with mass flow rates above the minimum flow rate limits established by Ciemat, there have been no cases of tube buckling due to poor cooling in neither the evaporator receiver tubes nor the superheater receiver tubes.

Another issue associated with DSG tubes is the coating required at 550ºC. Advanced coatings have to be evaluated for the higher operating temperature. New tubes have been installed in the last collectors of superheater field and the plant has operated at 550ºC for the past 4 months. The behavior of the material and coating at this target temperature will be analyzed as a part of the next tests. For this, Abengoa Solar is analyzing the technology at high temperature by means theoretical simulations with the main goal to demonstrate that the higher temperature will increase the global efficiency of the plant. Even though the thermal losses in the superheater solar field will be higher, these higher losses will be compensated for by an improvement in the efficiency of the power cycle.

During the evaluation period of these systems, no leakage or friction problems have been detected.

4. Analysis at 550ºC.

After the stability of the DSG trough technology was validated at 450 ºC, Abengoa Solar installed a new receiver tube and ball joints system to increase the working temperature up to 550 ºC. The higher temperature will increase the global efficiency of the plant. Even though the thermal losses in the superheater solar field will be higher, these higher losses will be compensated for by an improvement in the efficiency of the power cycle.

Currently, the prototype plant is working at 550ºC and after three operation months the results are as positive as they were at 450ºC.

Figure 4 is a graph with the main operation parameters during a clear day where the red line represents the superheater steam outlet temperature. As the overall trend in the temperature shows, the system has a great stability at 550ºC and a large thermal inertia during the shutdown of the plant**.**

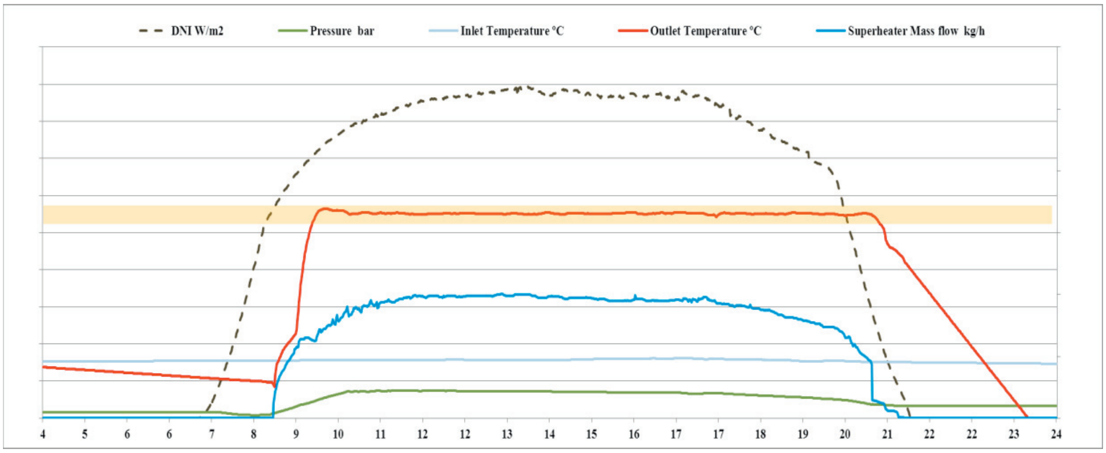

Fig.4 Operation during a clear day at 550 ºC

5. DSG TES system.

A major design consideration for parabolic trough power plants is thermal energy storage (TES) options. Currently the best option for DSG is the use of a steam accumulator storage system. A steam accumulator is a direct storage system eliminating intermediate equipment. It is based on the Ruth accumulator system where the steam is directly stored at high pressure in accumulator tanks.

The accumulator system is charged or filled with the saturated steam produced at maximum pressure from the evaporator solar field and this steam transfers the heat from the solar field to the water stored inside the tank. During the discharge process, the pressure inside the tank drops generating a flash evaporation of steam and this steam is sent to the turbine. This system allows for a very quick response from the storage medium, and will have a good performance during transients.

Any excess steam produced in the evaporator solar field will be used to charge the steam accumulators.

The accumulator system will be composed of several pairs of tanks depending on the desired storage capacity. This concept is very simple from an operational point of view.

Figure 5 shows a basic diagram of the plant with the steam accumulator storage system.

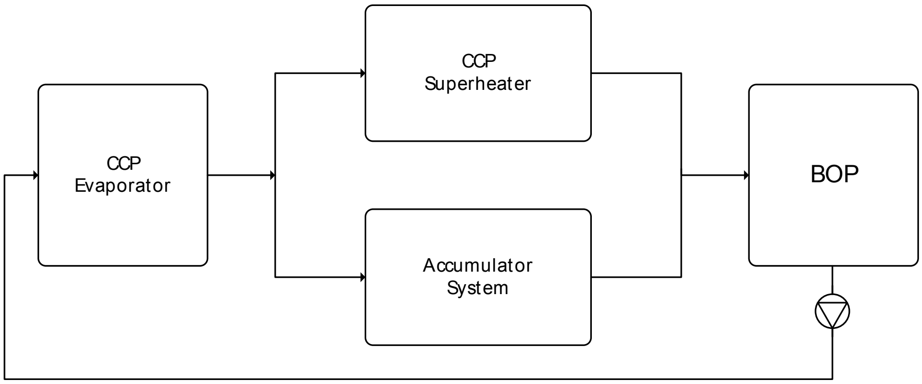

Fig.5. Scheme of a DSG plant with steam accumulator

6. DSG commercial plant.

With the theoretical model validated with experimental results from the demonstration plant Abengoa Solar has modeled commercial plants with different sizes, locations, and storage capacities in order to analyze the DSG impact in diverse scenarios. Figure 6 shows a flow chart of a commercial plant and Figure 7 shows the model's results for annual production of a 140 MWe plant.

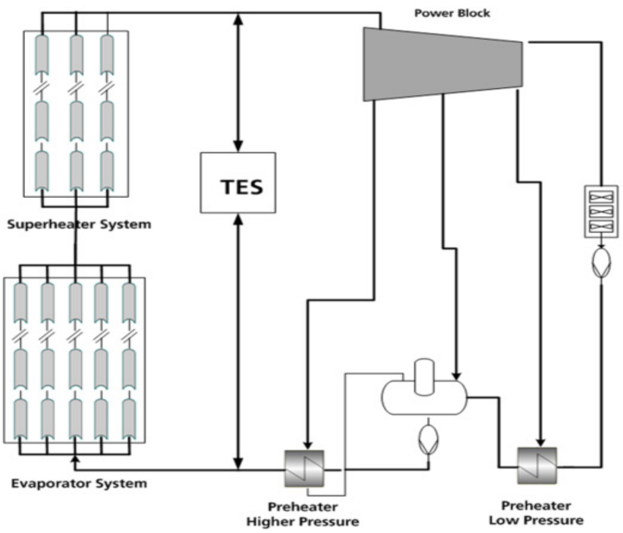

Fig.6 Flow chart for a DSG trough commercial plant

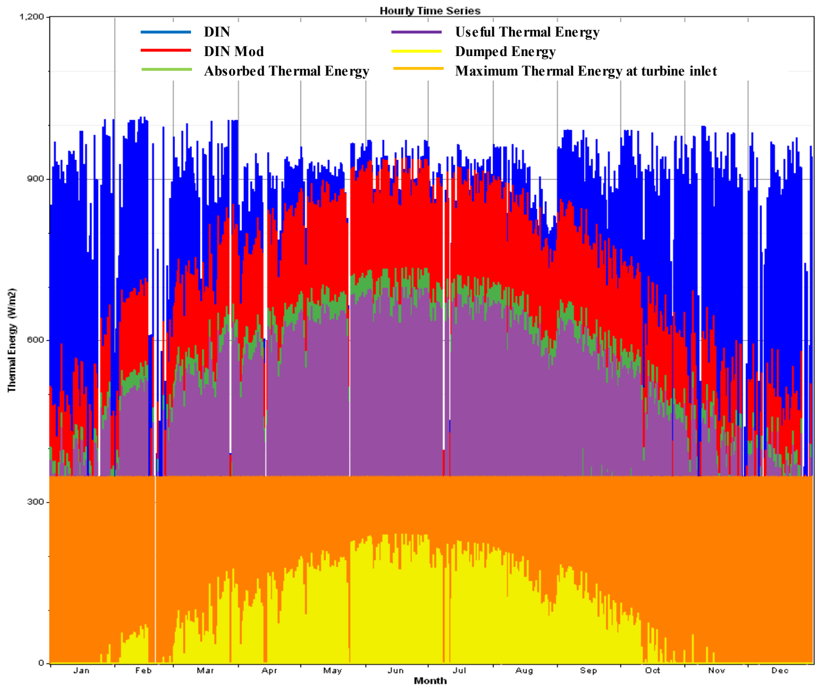

Fig.7 Annual production in W/m2

The main benefits of the DSG technology compared to the conventional technology, from a production point of view, are lower thermal losses and higher cycles efficiency. These benefits are a combination of the increased operation temperature, the smaller total solar field surface area required for the same power production, and the lower average HTF temperature. The average HTF temperature is lower due to the lower inlet temperature and the near constant temperature of the steam during evaporation. There is also a lower investment cost for DSG due to the reduced solar field area and the elimination of the oil/water steam generator heat exchanger train, expansion tank, and all the additional systems related to presence of oil HTF.

7. Conclusions.

As it has been shown in this paper, the most important technological challenges of the DSG parabolic trough plant such as the control stability, receiver tube viability, and collector interconnection feasibility have been analyzed and validated in the demonstration plant built by Abengoa Solar.

A performance model has been developed and validated during this project, increasing the reliability in the new DSG plants that will be installed in the near future and Abengoa Solar is developing innovative stored systems in order to improve the dispachability of the DSG technology.

References

[1] E. Zarza, (2004). Generación Directa de Vapor con Colectores Solares Cilindroparabólicos. Proyecto Direct Solar Steam (DISS). Editorial CIEMAT, Madrid.
[2] EckM. Zarza E. Solar energy 2003. Applied research concerning the DSG in parabolic troughs.
[3] Zarza Ed, González L, Rojas ME. Conceptual design of a 5 MWe DSG System.12th Solar Paces Mexico 2004
[4] Jürgen Birnbaum, Markus Eck, Markus Fichtner, Tobias Hirsch, Robert Pitz-Paal / Gerhard Zimmermann. A concept for future parabolic trough based solar thermal power plants . DLR (Stuttgart/Cologne)/Siemens (Erlangen). September 2008
[5] Jürgen Birnbaum, Markus Eck, Markus Fichtner, Tobias Hirsch, Dorothea Lehmann / Gerhard Zimmermann. A direct steam generation solar power plant with integrated thermal storage. DLR (Stuttgart/Cologne)/Siemens (Erlangen). August 2010
[6] James Spelling, Markus Jöcker, Andrew Martin. Annual performance imporovement for solar steam turbines throguh the use of the temperature maintaining modifactions. Department of Energy Technology, Royal Institute of Technology, Stockholm (Sweden). November 2011.