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THEORETICAL STUDY OF A DIRECT STEAM GENERATION POWER PLANT WITH PARABOLIC TROUGH COLLECTORS

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Abstract. *The Direct Steam Generation (DSG) is a Concentrated Solar Power (CSP) system that uses only water as the heat transfer fluid (HTF), instead of the two loops oil/molten salt topology used in almost all CSP plants. DSG works with different receiver technologies, being the most common solar towers, linear Fresnel receivers and Parabolic Trough Collectors (PTC). A still pending advance for DSG technology is the use of a Thermal Energy Storage (TES) to mitigate the intermittency of solar irradiance. Intermittency leads the steam generation and output power to vary along time. TES technology is applied in DSG systems in the form of steam accumulators, but experimental response of an operating TES was not found in the literature. In this sense, this work presents a simulation of a PTC power plant in order to size a TES composed of a steam accumulator and a hot water tank. After defining operational parameters as recirculation mass flow rate and design direct irradiation, two selected days were simulated, using measured solar data. The mathematical model simulated in Ebsilon attested that the integration of the hot water tank to the steam accumulator makes the pressure of the steam generated more constant over time.*

Keywords: *CSP, DSG, PTC, simulation*

1. INTRODUCTION

Solar plants have been increasingly studied to feed the public power grid in large solar fields. Photovoltaic cells were the forerunner of solar technologies popularization, due to their light systems that convert directly light to electricity. Along with solar plants popularization, other technologies have risen. One of these approaches concentrate the light and use its thermal energy to heat a fluid passing inside a tube, generating steam that goes through a thermodynamic cycle generating power, what characterizes such plants as Concentrated Solar Power (CSP) plants.

The first investments in large-scale CSP plants were made in the 1980s, when nine plants were built by Luz International in the southwestern United States. The name assigned to them was Solar Electric Generation Systems (SEGS), all use parabolic troughs as receivers, and have nominal power ranging between 13.8 and 30 MW. In 1991, the company went bankrupt (Wolff *et al.*, 2012).

Only in 2007, other CSP plants were built, by companies like Solargenix (Acciona Energía) and Solucar (Abengoa Group) (NREL, 2018; Wolff *et al.*, 2012). After the return of these investments, several plants were built around the world and some countries, such as Spain, already have considerable slice of the energy matrix coming from solar thermal plants. Among the four receiver technologies employed, the most used is the parabolic trough, followed by the solar tower which, despite the higher cost, will have its capacity increased in the coming years due to plants under construction in the United States (Burgi, 2013).

The called linear collectors are represented by linear Fresnel and parabolic trough collectors. Linear Fresnel are less expensive, take better advantage of the available area, and have minimized wind impact. In contrast, PTC collectors have higher optical efficiency and easier control of the tracking system. Such plants still have its development dependent of technical and economic assessment to certain regions, adapting existing systems and testing new approaches (Frein, 2017).

One of these approaches is the Direct Steam Generation (DSG), in which the fluid that absorbs the heat from the sun is water, that vaporizes, superheats and goes to a steam turbine. The DSG, compared to the ISG (Indirect Steam Generation),

works with higher steam temperatures (up to 500°C), and thus higher efficiencies, and has a lower complexity, because in ISG two fluids exchange heat, and for that a steam generator is located before the turbine. Other advantages are the minor impacts of a water leakage compared to an oil leakage and the fact the heat exchange happens mostly in a lower temperature (phase change temperature) compared to the maximum temperature, generating minor heat losses than from sensible heat fluids, as molten salts and thermal oils. Even so, molten salts are the most used as heat transfer fluids (HTF) of CSP plants due to their thermal stability at high temperatures and properties similar to steam. Meanwhile, DSG still has the inconvenience of carrying a two-phase fluid inside the absorber tubes, what requires a complex control system, high speed water flows to avoid the fluid stratification and very resistant tubes to support the turbine inlet high pressures (Giglio *et al.*, 2017).

Different from plants using thermal oil and molten salt, in DSG plants parabolic troughs are the least used receiver, with only one power plant in operation (TSE-1), located in Thailand, whose generation reports show a great variability in steam generation due to irradiation transients. For the TSE-1 tanks design, dynamic solar field simulations were performed by Hirsch and Eck (2006, 2008). The project considered water entering the collector field at 40 bar, and irradiation normal to the collectors of 200 W/m^2 during the start-up. The water not evaporated in the collectors during the start-up was calculated as 54% of the absorber tubes total volume, when simulating a 30 minutes preheating operation with incoming flow of 16 kg/s and 200 W/m^2 of irradiation normal to the collectors. For the same condition with higher flows, lower water volumes were generated. In spite of that calculation, the buffer hot water tank's useful volume corresponds to only 29% of the tubes volume, what cause the complete filling of the tank in the beginning of the day (Willwerth *et al.*, 2016).

DNI and day-to-day steam generation results show that the TSE-1 plant, despite using steam tanks, does not maintain the steam mass flow rate even for small variations of irradiation. When the irradiation decreases, the electric generation decreases almost at the same rate, and interruptions of irradiation of more than a few minutes cause the turbine to stop (Fig. 1). Because steam tanks are not sized to keep steam flow constant when there is no irradiation, they behave more like a steam flow damping system than a storage. On a day when the irradiation oscillates between low and high values, the tank reaches its maximum and minimum level consecutively (Khenissi *et al.*, 2015).

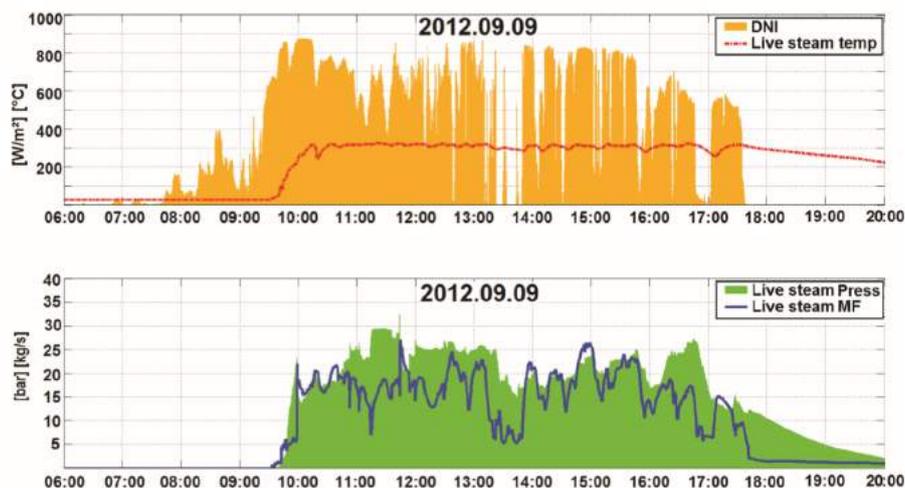


Figure 1. Steam mass flow, pressure and temperature in TSE-1 plant for a selected day
Source: Khenissi *et al.* (2015)

Many authors have been studying TES systems for DSG power plants of parabolic trough collectors and solar towers, for which the steam accumulator is the only commercially applied technology so far. Analyzing economically, DSG parabolic collector plants without thermal storage already have a lower energy cost than parabolic collector plants using thermal oil. When two 100 MWe plants are compared, an 8% less levelized cost of energy is achieved for the DSG plant compared to the conventional plant using oil. The disadvantage of the technology is the insertion of a three-tank thermal storage of molten salt and PCM with nine hours of storage capacity, which makes the cost of DSG technology 6% higher than the cost of thermal oil technology considering the same 100 MWe plant (Feldhoff *et al.*, 2012; Seitz *et al.*, 2017).

In order to test and achieve ways to avoid variable steam mass flow generation in a DSG power plant with PTC collectors, this work aims to study the principles behind the DSG scheme in a PTC field with recirculation operation. Once comprehended the basic behaviour of the plant, the work aims to simulate a collector field using components available in the market to size thermal storage tanks capable of maintaining constant steam mass flow. Simulations of the permanent operation states of the plant from five to five minutes are done in Epsilon to accomplish the objective.

2. CSP/DSG POWER PLANTS

Concentrated Solar Power (CSP), consists primarily of the reflection of the sun's rays at the same point or line through which a fluid passes that will heat up and bring heat to a power generation cycle or direct application of heat. CSP plants, of which Direct Steam Generation (DSG) is a type, use collectors to track the sun throughout the sun light period, in order to focus the radiation. There are four types of concentrator systems, collectors or receivers: parabolic troughs, linear Fresnel, central receiver towers and parabolic dishes.

Parabolic trough collectors (PTC) are the topic of study in this work. They are composed of rows of parabolic-shaped mirrors connected in parallel. This profile is responsible for reflecting the light incident on the focus, where the thermal fluid passes inside the absorber tube. A simple trough and its components are shown in Fig. 2.

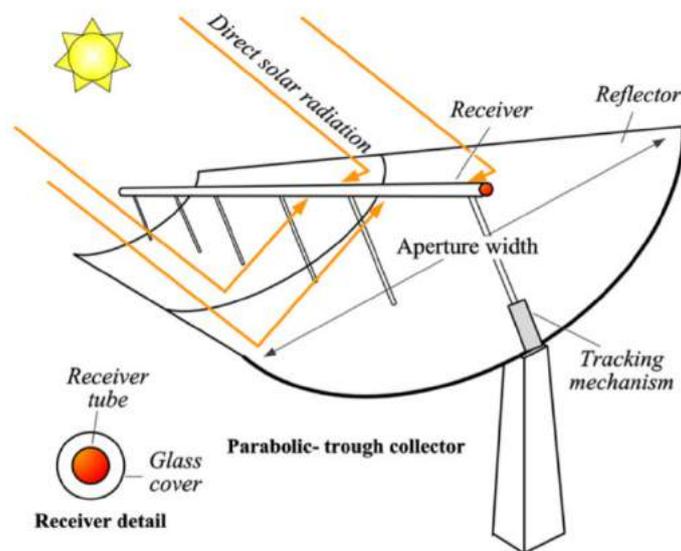


Figure 2. A parabolic trough and its components
Source: Cabrera *et al.* (2013)

Between the most important components, there are mirrors, absorber tubes and tracking system, without which the trough does not point in the direction of sun light. The mirrors have high reflectivity ($> 90\%$), low adhesion of dust, high resistance to heat and severities. They usually vary between 5 and 6 meters in width and between 12 and 13 meters in length, and are usually manufactured from glass (0.8 to 5 mm) (Bianchini, 2013).

The absorber tubes are mounted to the focal line of the trough. With a diameter of approximately 70 mm, they are made of stainless steel painted with an anti-reflective coating to improve the absorption of the radiation, and are inside a glass tube. Between glass and steel is sometimes left vacuum, as yet another measure of avoiding heat losses. (Bianchini, 2013).

The orientation of the trough towards the sun is usually made by electric motors or hydraulic units. The movements can be on only one axis or two axes. When on only one axis, the movement can occur on the east-west axis, north-south, or on an axis parallel to the Earth's axis. The most common sun tracking occurs from east to west with the trough installed in the north-south direction or the opposite. The north-south oriented collector can collect more heat than east-west oriented, but with less uniformity throughout the year, as it collects more heat in the summer and less in the winter (Kalogirou, 2009).

2.1 Heat Transfer Fluids (HTF)

The working fluid carries enthalpy that, after transferred to the water, is converted in mechanical energy into the steam turbine. In Direct Steam Generation, the working fluid is water, and the heat is transferred to the water in the collectors, while in Indirect Steam Generation, the working fluid exchanges heat with water after passing through the collectors and before the steam turbine. In both case, after delivering its heat, the working fluid returns to the collectors.

Heat Transfer Fluids (HTF) have a high thermal capacity. Most plants in operation still use synthetic thermal oils. They operate up to a maximum temperature of approximately 400°C , which limits the efficiency of the power block. In addition, it also has a fast aging, as around 4% of the volume needs to be changed every year, and has an expensive cost, which amounts to up to 5% of the cost of the plant (Giglio *et al.*, 2017).

As a way of getting around some of these problems, mixtures of salts such as NaNO_3 and KNO_3 have been used in

some plants. They have a thermal stability up to 550°C, which allows higher efficiency, has a lower cost than thermal oils, and avoids the use of the heat exchanger in the thermal storage system (TES) the salt itself being the storage fluid. On the other hand, the salt also presents disadvantages, such as high solidification point (220-250°C) and high level of corrosion at high temperatures (Giglio *et al.*, 2017; Khenissi *et al.*, 2015).

Direct steam generation (DSG) is a special type of solar concentrator plant in which the HTF is water, that goes through collectors, evaporates, superheats, expand in a steam turbine, and starts the cycle again without exchanging heat with other fluids. This operation enables higher steam temperatures than those achieved by oils, up to 500°C. This causes the efficiency of the system to increase, and therefore the investment decreases. Another factor that diminishes the investment is the reduction of the system complexity, because when the generation of steam is indirect (ISG), two fluids and a steam generator are necessary before the turbine (Giglio *et al.*, 2017).

In DSG, most of the heat is transferred in the phase exchange, which occurs at a low temperature compared to the maximum temperature, which results in lower thermal losses than sensible heat working fluids such as molten salts and thermal oils. Environmental and safety risks also decrease when considering the reduced impacts of a water leak compared to an oil leak, a lower freezing point than the oils, and a lower corrosion potential than the salts (Fernández-García *et al.*, 2015)

Still, molten salt mixtures are the most promising candidates as heat transfer fluids from solar power plants because of their thermal stability at high temperatures, water vapor-like properties, and heat storage systems using commercially available molten salts, which allow direct storage of the working fluid. Meanwhile, DSG technology has the drawback of having a two-phase fluid flowing through the absorber tubes, which introduces technical difficulties in flow control, tube fabrication and makes the operation even more complex when variations in solar irradiance occur. A complex control system and the use of high velocity water streams is necessary to avoid stratification of the fluid, and the pipes must be resilient to withstand the high inlet pressure of the turbine (Giglio *et al.*, 2017).

2.2 DSG plants in operation

The first project in real solar and scale conditions was Direct Solar Steam (DISS), carried out at the Plataforma Solar de Almería (PSA) in the city of Almería, Spain, between 1996 and 2002. The project had the objective of optimizing collectors and operation and maintenance procedures, and was divided in two parts, one to design and build a line of parabolic collectors, and one to study the control and stability of steam generation in the line built. With the tests, it was possible to improve the start-up and shutdown operations and study the effect of the collectors slope on their thermal performance (Giglio *et al.*, 2017).

The test plant built in this project consists of a line of eleven 2 MWt PTC oriented on the north-south axis, capable of producing 0.8 kg/s of steam at 100 bar and 370°C. The collectors were assembled in a region of favorable solar irradiance and the plant generates power in a closed cycle at different pressure levels (30, 60 and 100 bar) (Oliveira, 2013). Different operating modes for a direct steam generation plant in parabolic linear collectors were defined and compared in this test plant. They are the mode with recirculation, the injection mode and the single circulation mode, and are represented in Fig. 3. It is seen that the injection before the last manifold takes place in all modes, and that only the recirculation mode needs a steam separator. With the tests, it was verified that the operation in recirculation mode is the best for a commercial plant, because it allows a more effective control of the steam produced. It was also concluded that further testing was required to attest to the feasibility of single circulating operation (Eck *et al.*, 2003).

In the second half of the 2000s, Solarlite CSP Technology GmbH, a German company, built pre-commercial DSG plants in Spain and Thailand. By gaining experience, they started to build the first commercial plant using DSG technology in parabolic troughs, in 2010. This plant, named Thai Solar One (TSE-1), is in Thailand and belongs to Thai Solar Energy Co. Ltd. (TSE), which is an operator and maintainer (Fig. 4). With an investment of 20 million euros, the plant works in a recirculation mode with twelve lines of collectors in the evaporation section, seven lines of collectors in the superheating section and a central steam separator between these two sections. The steam flow is stable for days with stable or partially variable DNI. However, for days with highly variable DNI, flow instabilities between the lines and local overheating incidents were reported (Giglio *et al.*, 2017; Khenissi *et al.*, 2015).

Currently, this is the only commercial parabolic trough plant in operation that applies DSG technology. Another eight DSG commercial plants have also started operation in recent years, using Fresnel linear reflector technologies and solar towers, and are summarized in the Tab. 1. Solar tower correspond to five of the nine commercial plants and is the fastest growing technology, because they can reach temperatures higher than parabolic troughs and have more cost-effective storage systems. However, they require a size of at least 100 MW to be economically viable (NREL, 2018; Sulyok, 2014).

2.3 Thermal Energy Storage (TES)

All CSP plants have to use a thermal energy storage (TES), a backup fuel burning, a defocusing system of the collectors or a combination of them, in order to keep a constant steam production and, consequently, energy generation. This need is due to the intermittent sun irradiation. The TES system dispense the others, making it possible to use the solar energy

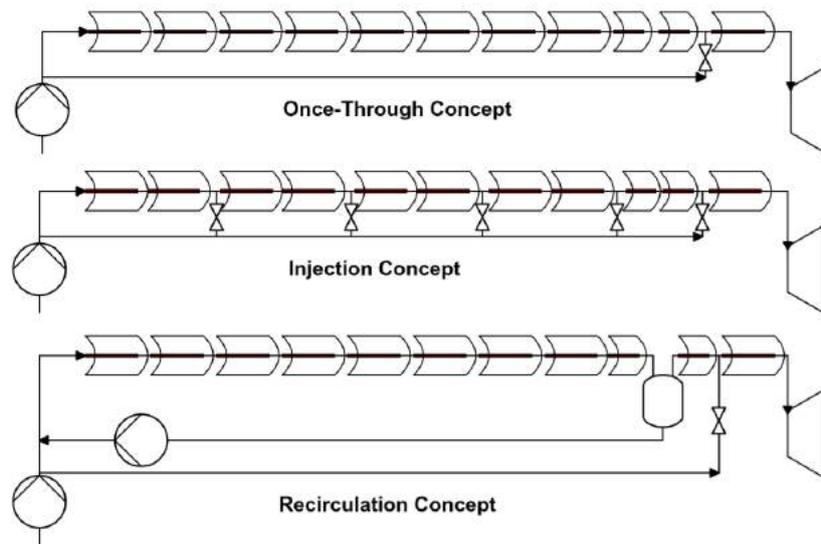


Figure 3. Operation concepts of a line of Parabolic Trough Collectors
Source: Valenzuela *et al.* (2005)



Figure 4. View of TSE-1 plant, in Thailand
Source: Willwerth *et al.* (2016)

at a time different from the irradiation, thus allowing to generate power during the night and maintaining a constant power or power control to follow the energy demand for each hour of the day. Apart from that, different from a steam generator burning fossil fuel, a TES preserves the renewable characteristic, valuable to earn carbon credits (Giglio *et al.*, 2017).

In an economic analysis, DSG PTC plants without thermal storage already have a lower energy cost than parabolic collector plants using thermal oil. When two 100 MWe plants are compared, an 8% less cost level is achieved for the DSG plant compared to the conventional plant using oil. The disadvantage of the technology shows up when a three-tank thermal storage of molten salt and PCM with nine hours of storage capacity is inserted in the two 100 MWe plants, which makes the cost of DSG technology 6% higher than thermal oil technology (Feldhoff *et al.*, 2012).

TES systems increase the investment both by adding the systems and by increasing the field size, but its costs are compensated by the increase of the hours in which energy is generated and control of production to approach the energy demand for each hour of the day. The costs of such systems should be low enough to reduce the levelized cost of energy and increase the profits. Also to reduce the costs, an alternative so that it does not need the increase of the area of the collectors is the use of a hybrid system (Bianchini, 2013).

If energy is stored, more heat is produced than is converted in electric power. This ratio of energy from the solar field to the energy required to operate the turbine at maximum load is called solar multiple (SM). The optimization of this value is necessary because defining it simply as one means that the solar field will deliver the nominal capacity of the turbine,

Table 1. DSG plants in operation worldwide

Plant	Collector type	Nominal pow. (MW)	Nominal pres. (bar)	Nominal temp.(°C)	TES type	TES time (h)	Start of operation
Planta Solar 10	ST	11	45	250-300	Steam Accum.	1	2007
Planta Solar 20	ST	20	45	250-300	Steam Accum.	1	2009
Khi Solar One	ST	50	-	-	Steam Accum.	2	2016
Ivanpah Solar	ST	377	160	550	-	-	2014
ACME Solar Tower	ST	2.5	60	440	-	-	2011
Thai Solar Energy 1	PTC	5	30	340	-	-	2012
eLLO Solar Thermal	LFR	9	70	285	Steam Accum.	3	2018
eCare Solar Thermal	LFR	1	70	280	Steam Accum.	2	-
Puerto Errado 1	LFR	1.4	55	270	Steam Accum.	-	2009
Puerto Errado 2	LFR	30	55	270	Steam Accum.	0.5	2012

Sources: NREL (2018); SIEMENS (2011); SUNCNIM (2016); Zarza (2016); González-Roubaud *et al.* (2017); Khenissi *et al.* (2015)

being able to oscillate between smaller and larger values throughout the year, undesirable from the point of view of the turbine. Therefore, some plants, even without storage, have the solar multiple a little higher than 1 as a way of producing enough energy for the turbine to operate at its maximum efficiency (Bianchini, 2013).

Different technologies are used in CSP plants in operation. These include phase change materials (PCM), thermocline, solid storage materials, molten salts and steam accumulators. In commercial DSG plants, only steam accumulators have been applied as thermal storage so far. Regardless of technology, storage types can be separated in the following types: chemical, sensitive and latent. Very few demonstrations of chemical storage have occurred, and so only the other two are discussed here.

Latent and sensitive storage are complementary in the sense that their combination offers advantages over their separate application. For plants with single-phase fluid (molten salt, oil, air), sensitive storage is generally preferred and the choice of options is given from the application temperature range. For plants with two-phase fluid, such as the water-vapor mixture, latent storage is preferred, by storing energy from the fluid over a narrow range of temperatures. Sensitive storage should not be applied here because the discharge pressure is much lower than the pressure at which the tank is loaded, causing efficiency losses. An exception to this restriction is given to steam accumulators, where saturated or slightly overheated steam charges the tank by increasing the sensitive energy of the pressurized water therein (Lovergrove and Stein, 2012).

The steam accumulator is a tank that stores hot saturated water. It is charged with steam by injectors located in its bottom at a higher pressure. When the steam needs to be discharged, a valve in its top opens and the pressure drop of the water promotes its evaporation and steam discharge at a lower pressure, until a minimum level is reached. The main disadvantage of the accumulator is the steam is discharged at a lower pressure than the pressure it was charged, meaning an energy loss and an ineffectiveness in promoting a continuous discharge to the turbine. (González-Roubaud *et al.*, 2017).

Steam accumulators are the only TES commercially applied technology in DSG plants. Table. 1 shows that almost all the plants operating use accumulators. Two exceptions are Ivanpah Solar, that does not need a TES because of a backup natural gas burning system, and TSE-1, because it is a small plant with not such a huge reliable generation impact (González-Roubaud *et al.*, 2017).

TSE-1 has a hot water tank between the evaporation and the superheating sections, with both functions of steam separator and buffer system. Its buffering capability does not allow that sudden variations in steam generation in the evaporation section arrive in the turbine, keeping components from harmful transients. This makes the steam accumulator unnecessary for achieving an unreliable but safe production (Willwerth *et al.*, 2016).

3. METHODOLOGY

3.1 Configuration

The configuration simulated is shown in Fig. 5. The layout is composed of three sections. the evaporation section is a line of PTC collectors of the model ET-100 with absorbers of the model PTR70 oriented in east-west direction. The storage section is composed of three storage tanks. Finally, the superheating section is also a line of the same PTC collectors and absorber tubes. The lines are presented with a random number of collectors, to be merely illustrative. In fact, the number of collectors vary between the simulations.

The collectors operate applying the recirculation concept, that has been proved the best configuration choice for DSG

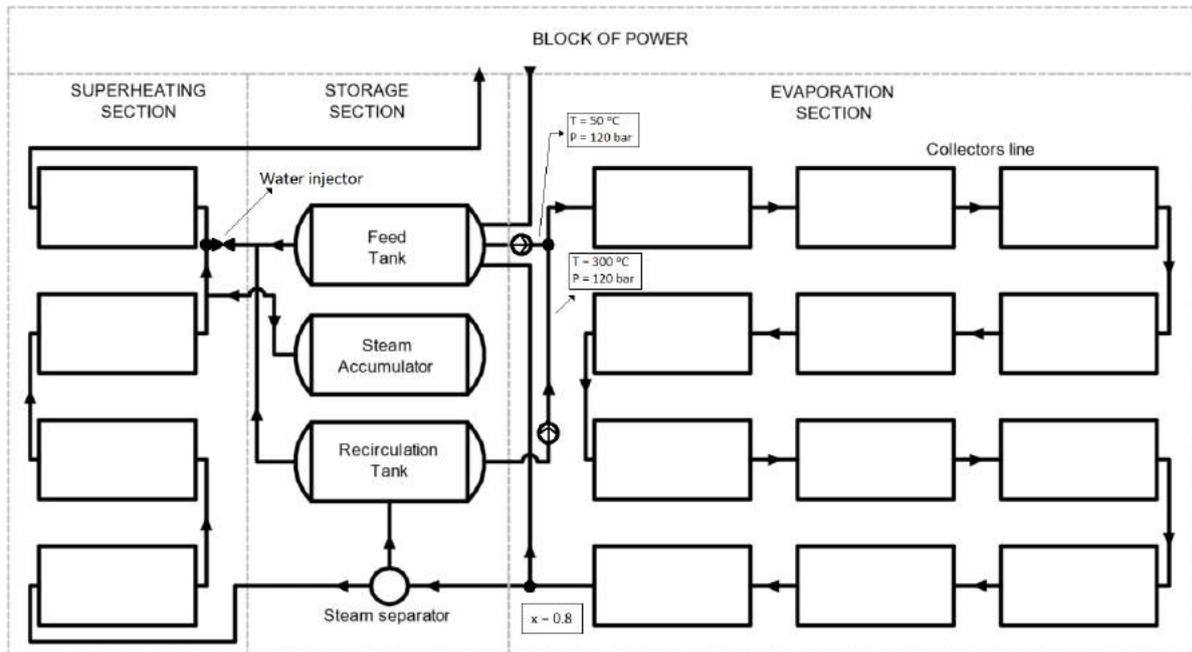


Figure 5. Layout of collectors field

plants. In this concept, the water not evaporated recirculates immediately to the beginning of the collectors line, but here the liquid not evaporated is stored in the recirculation tank so as to be used in specific periods.

The proposed work is to test the plant with a recirculation tank, besides the steam accumulator, already used in some commercial DSG plants. The recirculation tank stores the liquid not evaporated in low irradiation periods, to mix with the feed tank water and go through the collectors, working as a support in intermediate irradiation periods. In high irradiation times, the collectors discharge steam to the turbine, and the surplus charges the steam accumulator, while in low irradiation times the accumulator discharges steam to the turbines, at a lower pressure than the collectors. The intention using the recirculation tank is to increase the duration of the turbine operation with the steam discharged by the collectors, that operate in a higher pressure.

This operation is called here controlled recirculation, once recirculation tank and steam accumulator are discharged at different times according to the DNI incident to the collectors (DNI_{op}). The plant design steam mass flow rate is the amount the evaporation line produces with no recirculation flow at the design DNI (DNI_{dmax}). This design value also considers that there is a minimum DNI (DNI_{dmin}) which can still produce the same amount of steam at a recirculation flow that maximizes the steam production.

For a day without clouds and clear sky, characteristics of a good portion of days in the year, the following operation is adopted:

- Part I: Steam accumulator discharges while the collectors don't generate steam. In the beginning of the day, this is the preheating time.
- Part II: If $DNI_{op} < DNI_{dmin}$ and time < 3 pm, the steam accumulator is discharged and the collectors still don't produce steam. The temperature at the end of the evaporation line is controlled to be the saturation temperature, so that the collectors are preheated and the recirculation tank is charged. When the saturation temperature is not feasible, the flow coming out the steam separator is diverted to the feed tank.
- Part III: If $DNI_{dmin} \leq DNI_{op} \leq DNI_{dmax}$, the recirculation tank is used to control the steam mass flow rate, and all the steam produced by the collectors goes to the turbine. The steam accumulator does not operate.
- Part IV: If $DNI_{op} > DNI_{dmax}$, the steam produced by the collectors goes to the turbine and to charge the steam accumulator. The collectors operate in immediate recirculation.
- Part V: If $DNI_{op} < DNI_{dmin}$ and time ≥ 3 pm, the collectors operate generating the maximum possible steam. The recirculation tank and steam accumulator are discharged. The accumulator stops discharging when it reaches the same level it started the day with, and the recirculation tank stops discharging when it reaches the same level it started the day with or if the irradiation is not enough to generate steam, what happens first.

The states of operation divided in these five parts oscillate instantaneously, and an operation day with high irradiation and no irradiation variability goes through the parts in the following order: I-II-III-IV-V. Only if the irradiation suddenly falls or stops, the plant can go back from part IV to part III, II and I.

In part V, the maximum possible steam is produced by the collectors, if it is later than 3 pm and the DNI falls below a determined value. This is done in order to empty the recirculation tank while the DNI is high enough for that. In all the parts, no recirculation and controlling the outlet saturation temperature prioritize the recirculation tank charge, the recirculation that produces the maximum possible steam charges the accumulator and discharges the recirculation tank, and an immediate recirculation charges only the accumulator, while the recirculation tank is kept idle.

The accumulator starts discharging on a fixed local time (8:00 am), as it does not depend on the weather, and stops discharging when its initial state is reached. The recirculation tank starts being charged in part II, as soon as the collectors are capable of generating water at the saturation temperature, and are discharged in parts III and V.

A configuration without the recirculation tank, used in commercial DSG plants, is also simulated and compared to the previous. In this operation, called here immediate recirculation, the recirculation of the water not evaporated happens immediately after the water and steam are separated at the end of the evaporation line.

3.2 Modeling

To calculate the angle of incidence (θ_i), the model receives azimuthal angle (0° for north-south axis), tilt angle (0° horizontally), time, date, latitude, and longitude. The incidence angle is calculated according to Duffie and Beckman (1991). A correction value (C) of the irradiation that reaches the collector is recommended for the collector ET-100 and calculated by Eq. (1) and the energy balance is given by Eq. (2) (STEAG, 2018).

$$C = 1 + 0.00010596\theta_i - 0.00017091\theta_i^2 \quad (1)$$

$$Q_{effective} = DNI_{op}\eta_o ACFSLBW - Q_{loss} = \dot{m}(h_o - h_i) \quad (2)$$

Where DNI_{op} is the normal irradiance to the collector, A is the effective opening area of the collector, η_o is the optical efficiency of the collector, C is the correction value of the angle of incidence, F is the focusing factor, S is the shadow factor, L is the cleaning factor of the mirrors, B is a reflection loss factor at the edges of the collector, W is a factor of optical losses due to the impact of the wind, Q_{loss} are the heat losses, m is the mass flow of the solar field, and h_o and h_i are the enthalpies of the inlet and outlet fluid of the solar field. $Q_{effective}$ represents the effective heat received by the fluid throughout the collectors line (STEAG, 2018).

Heat losses published for the ET-100 collector and reported by the software are proportional to the square of the difference (dT) between fluid temperature and ambient temperature. They are calculated by Eq. (3) and do not consider the wind speed (STEAG, 2018).

$$Q_{loss} \left[\frac{W}{m^2} \right] = 0.00047 \left[\frac{W}{m^2 K^2} \right] (dT)^2 [K^2] \quad (3)$$

Pressure losses are calculated by a correlation of Friedel (1979), which considers uniphasic and biphasic flows. This model does not consider the roughness of the tube. As models for pressure loss of biphasic streams that consider roughness are not available, the Swamee and Jain (1976) model for single-phase flows is used for each phase present, and the pressure loss approximation is calculated as a sum of losses of each phase. The biggest calculated pressure drop between Friedel (1979) and Swamee and Jain (1976) is adopted (STEAG, 2018).

3.3 Model evaluation

The results of Zarza *et al.* (2006) were used to validate the model constructed in Epsilon. This work is the result of the Inditep Project, for the design and simulations of a DSG plant. The designed plant has two sections of collectors with seven lines of collectors each, six collectors per line in the evaporation section, and two collectors per line in the overheating section. Steam separators at the end of each evaporation line separate the steam going to the superheating section of the liquid that is directly recirculated. Water injectors before the last collector control the temperature of the steam arriving at the turbine. The collectors used are the same as this one and the absorber tubes are an earlier version of those used here, having a lower working pressure limit.

The charts of Fig. 6 and Fig. 7 illustrate the results of Zarza *et al.* (2006) compared to the simulations, corresponding to January 29th 2005 and June 12th 2005 for the city of Almería, Spain. With this comparison, the ability of the model to calculate steam generation and electric generation for a parabolic-cylindrical collector plant is attested. proposed in the Inditep project is made difficult by the lack of specification of some parameters in the available literature. It can be seen that the power results were very close over the two days. Regarding the mass of steam and thermal power, the results of the model were slightly above the Inditep Project over the two days. This may be a consequence of loss factors not

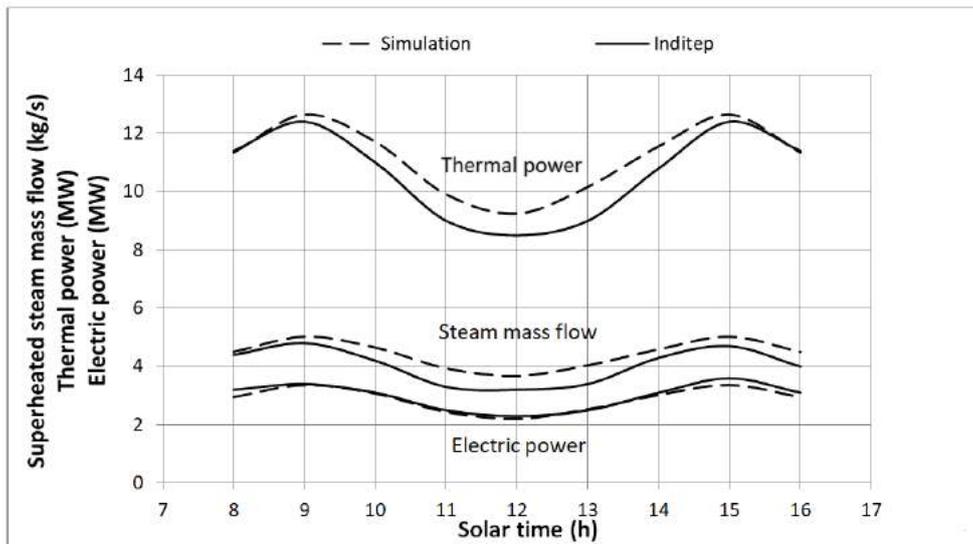


Figure 6. Simulation and Inditep results for January 29th 2005 in Almería plant, Spain

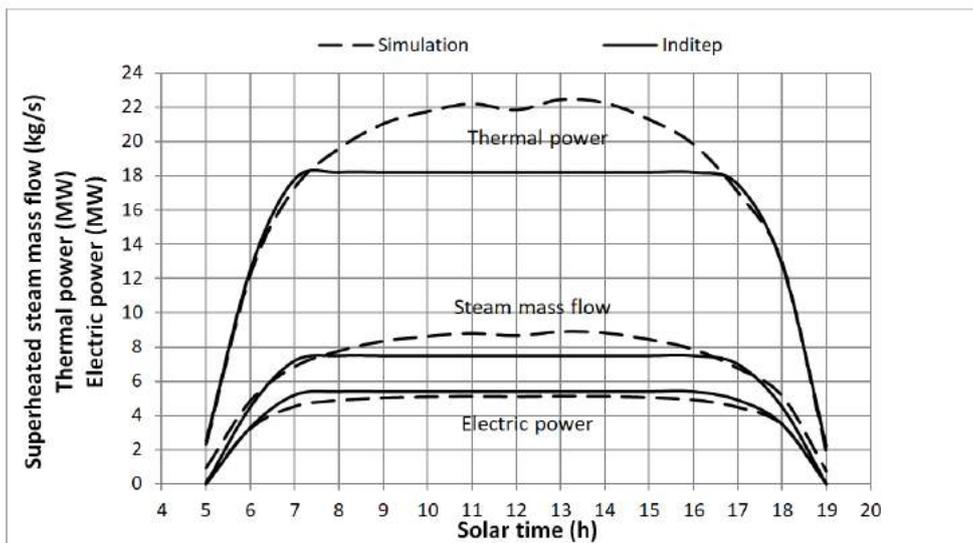


Figure 7. Simulation and Inditep results for June 12th 2005 in Almería plant, Spain

considered. The works of Oliveira (2013), Fraidenraich *et al.* (2013), Xu and Wiesner (2015) and Guo *et al.* (2016) also tried to reproduce the results of this project, and reported the same difficulty. The most recurrent justification is the turbine efficiency drop, which was not considered for partial loads in the Inditep Project.

On June 12th 2005, one notices how the projected plant uses a system, which was not specified in the work, to limit its steam production and consequent energy generation. It is assumed that this system is to defocus some collectors (assumption of Oliveira (2013)) or flow control valves at the entrance of each line. The present work attempted to reproduce this system with the flow control in each line based on a constant steam quality at the entrance of the steam separators. This strategy reproduced the control of power limit of the Project, generating, however, steam flow and thermal power a little higher than expected in the intermediate hours of the day (Fig. 7).

The control of the steam quality even on January 29th 2005, which does not need this control, because it is a winter day, produces thermal power and flow a little larger than in Inditep (Fig. 6). Nevertheless, in these days the electric power is very close to Inditep, and in summer it has a constant maximum value, which shows that the control of the steam quality at the exit of the evaporation section seems to promote a power limitation, as in Zarza *et al.* (2006).

The differences between the results are justified by the power limitation system and the provenance of the liquid that is injected into the superheating lines, both not specified in the work. Another difference of the work is that Inditep performed simulations every 5 minutes, while here only one simulation per hour.

3.4 Simulation

It is assumed that the collectors lines are in thermal equilibrium, heat losses in the pipes between the components are ignored and pressure losses in all components are calculated based on nominal losses. Climatic conditions are treated as a series of permanent states. All lines are treated equally, without considering different dominant radiating or transient lines in different parts of the solar field. The simulation is in a quasi-permanent regime and, therefore, a mere approximation, due to the variable character of the solar irradiation in time and space.

The measured DNI data are treated so that the water-vapor mixture arriving at the steam separators and the steam arriving at the turbine at each time interval are based on the irradiation corresponding to their entire residence time in the tubes, extending to previous time intervals. For this, an iterative process is performed in each simulated time interval, explained in the flowchart of Fig. 8.

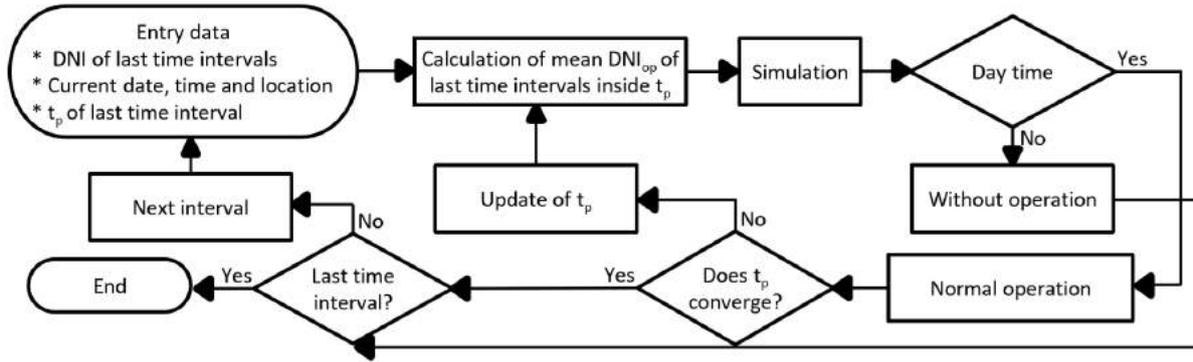


Figure 8. Flow chart of the algorithm implemented for the quasi-steady simulation

Given an estimated residence time t_p , the DNI_{op} is calculated as the average of the values of DNI corresponding to the previous intervals that occurred within the residence time. The simulation is done using this DNI_{op} , and the feed and recirculation flows calculated by the simulation are used to calculate t_p and update its value to recalculate the DNI_{op} until its value satisfies a convergence criteria. In each iteration step, a new t_p is calculated with Eq. (4), where N_{col} is the number of collectors per line, L_{col} is the collector length and v is the flow speed.

$$t_p = \frac{N_{col}L_{col}}{v} \quad (4)$$

The simulations of the controlled recirculation and immediate recirculation schemes are done for two selected summer days of 2017 in order to estimate the tanks sizes for each day and operation scheme. The tanks states are not calculated, but considered constant. The algorithm of Fig. 8 is used for the calculation of a DNI that considers the residence time and smooths the measured data transients.

The strategy adopted here is simplified to one day considering the charge/discharge process is done in cycles of no more than one day. In this way, the tanks start the day with only a small portion of their working volume charged, avoiding the heat loss along the night, and have similar charging and discharging amounts over the day. Thus, one very representative day of the average DNI profile of a year should be enough data to estimate the tanks sizes.

4. RESULTS

The increase in recirculation mass flow is able by itself to maintain the steam mass flow rate down to a certain DNI value for each design DNI. Figure 9 shows the irradiation ranges for which the recirculation tank is capable of maintaining the steam flow constant.

$DNI_{dmax} - DNI_{dmin}$ covers only a small part of the whole DNI range, what makes the recirculation tank responsible for the constant steam mass flow of only a small fraction of time. Elevating the design DNI more to enlarge this interval is not possible for Belo Horizonte conditions, in which the operation DNI does not usually overpass 1000 W/m^2 . Considering 400 W/m^2 as the design DNI, the maintenance of the design steam mass flow (0.56 kg/s) is desired during the whole operation. Figure 10 shows measured and calculated DNI values for each time interval simulated.

It can be noted how calculating the DNI as the average of the last time intervals smooths the DNI curve, and represent more faithfully the plant absorption of irradiation transients. The behavior of steam temperature was not sensitive to the DNI variation, and kept constant through the operation simulation, except when the plant is preheated. Figure 11 shows the simulation results of the controlled recirculation scheme.

Between 7 and 8 am, the recirculation tank is charged while the collectors are preheated and no steam is discharged to the turbine. Close to 9 am, the recirculation tank starts to discharge, to keep a constant steam generation, followed

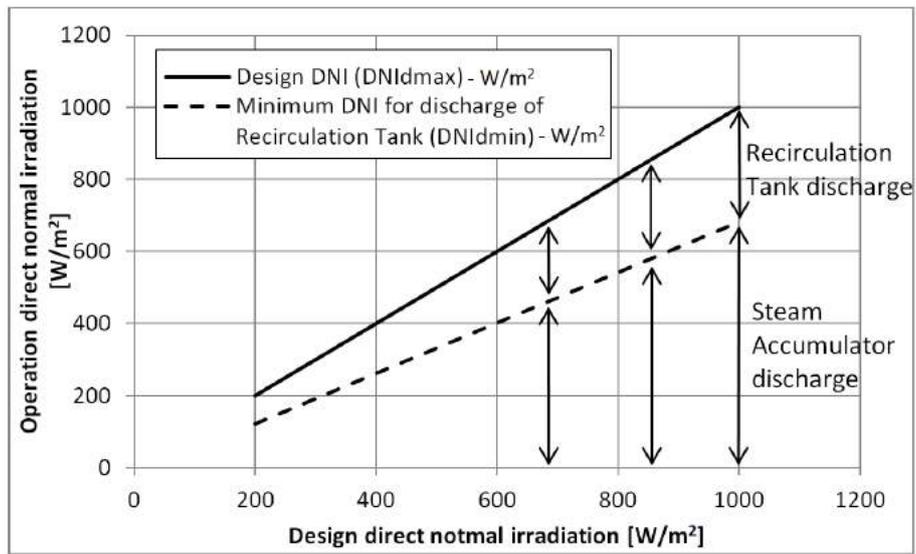


Figure 9. Ranges between DNI_{dmax} and DNI_{dmin} , in which the steam mass flow control is possible solely with recirculation mass flow

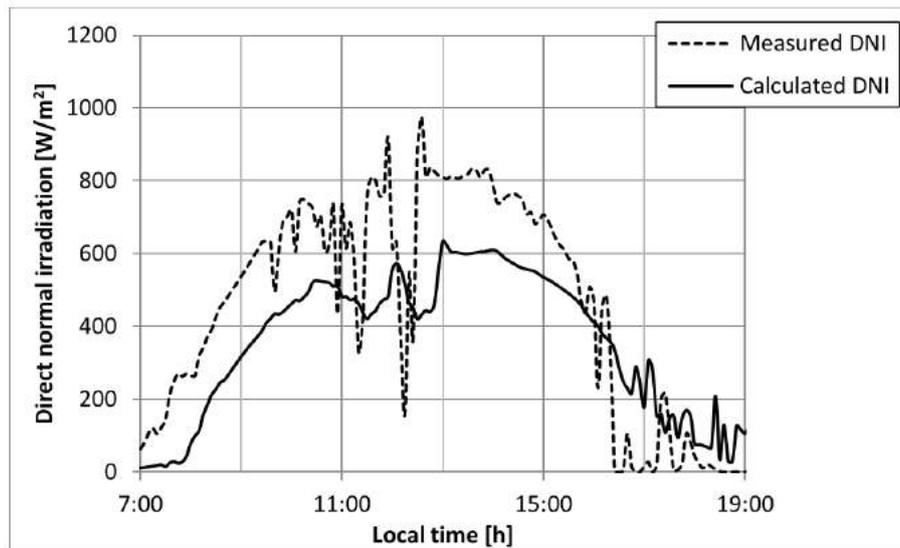


Figure 10. DNI calculated as the average of the time intervals inside the flow residence time, for the design DNI of 400 W/m^2 on January 1st, 2017

by an immediate recirculation period, while the DNI is big enough to charge the steam accumulator. Only when the irradiation falls, the recirculation tank leave its idle state. If the irradiation maintains high until the end of the day, like in the simulated day, it is discharged at the end of the day only to stretch the accumulator discharge time.

Figure 12 shows the simulation results of the immediate recirculation scheme. Between the curves, there are steam mass flow generated by the collectors, the constant steam mass flow discharged to the turbine (the same of Fig. 11), along with the charged and discharged amounts of the steam accumulator for the operation in immediate recirculation.

In Fig. 12, the collectors preheating happens but the steam generated in the beginning of the day charges the accumulator, instead of the recirculation tank. With that, the accumulator is charged and discharged at the same time and a smaller steam accumulator tank is required. The period while the steam mass flow is below the constant generation line is when the accumulator is charged and discharged at the same time. The period while the steam mass flow is above the constant line is when the steam goes directly to the turbine and the accumulator is only charged with the surplus steam.

The steam accumulator curves of both Fig. 11 and Fig. 12 represent the charge and discharge mass flows. The charge amount equals the discharge amount, considering an average efficiency of 0.8. The tanks levels are calculated taking into account the amount entering the tanks is decreased by this value. Figure 13 shows the cumulative charged/discharged amount for the same day, operating with immediate and controlled recirculation. The tanks start and finish the day with

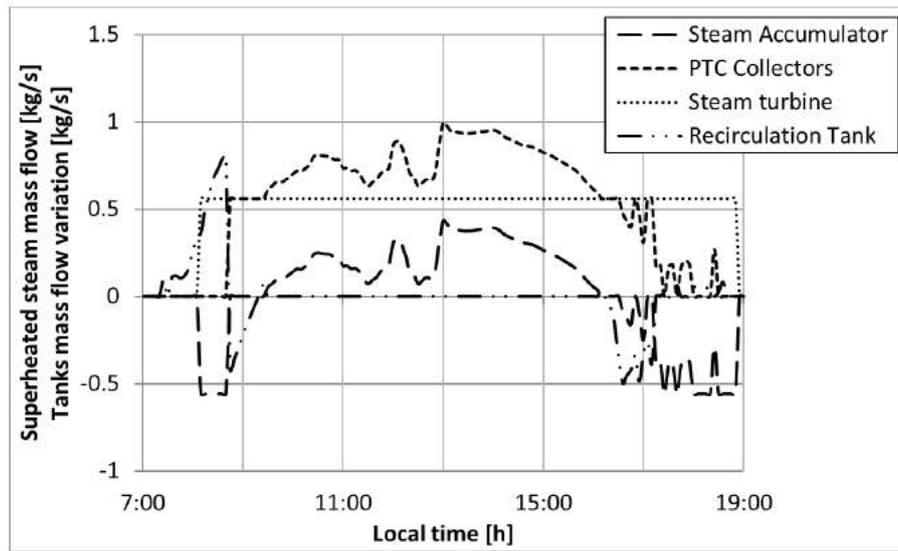


Figure 11. Steam mass flow in and out the tanks, steam mass flow generated by the collectors, and steam mass flow discharged to the turbine, for the design DNI of 400 W/m^2 in controlled recirculation operation on January 1st, 2017

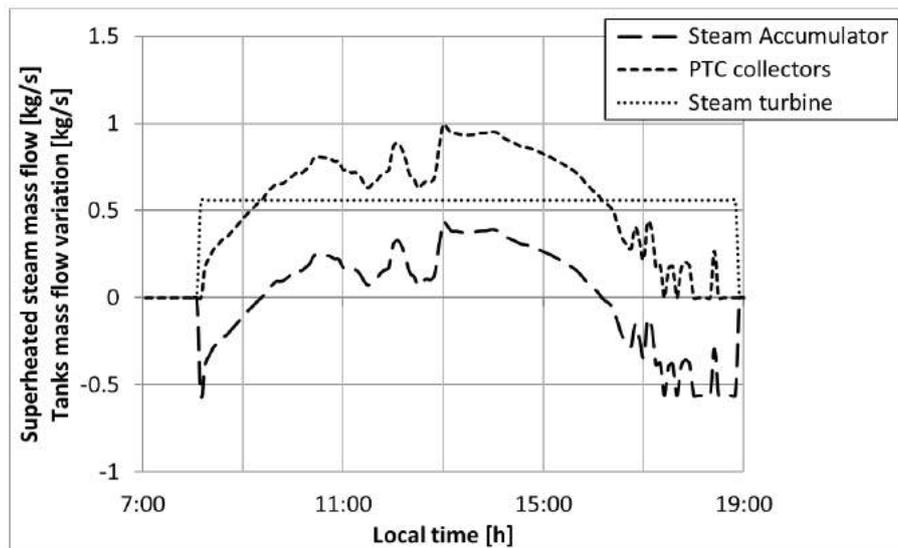


Figure 12. Steam mass flow in and out the accumulator, steam mass flow generated by the collectors, and steam mass flow discharged to the turbine, for the design DNI of 400 W/m^2 in immediate recirculation operation on January 1st, 2017

the same level, as intended.

In comparison to these results, a second day is simulated. Now, a high DNI variability summer day is chosen. Figure 14 shows measured and calculated DNI values for that day with the same design DNI of the last day.

To accomplish the controlled recirculation and immediate recirculation schemes for the two days simulated, the working volume is estimated for the steam accumulator and the recirculation tank. The estimates are shown in Tab. 2. As can be seen, the operation in controlled recirculation with a $\text{DNI}_{dmax}=400 \text{ W/m}^2$ lasted 10:45 hours with 8:05 hours in high pressure, while the operation in immediate recirculation lasted the same 10:45 hours with only 6:35 hours in high pressure, on January 1st. The difference between the schemes simulated in the second day was bigger, justifying even more the recirculation tank to be used in the plant.

With $\text{DNI}_{dmax}=300 \text{ W/m}^2$, the solar field produces a smaller steam mass flow but has an extended generation, with extended high pressure discharge time, observed for both days. It is also observed that decreasing the DNI_{dmax} makes the required steam accumulator bigger and the required recirculation tank smaller.

The main advantage of the immediate recirculation is that no recirculation tank is required and a simpler control can be implemented. The main advantage of the controlled recirculation scheme over the immediate recirculation is that the

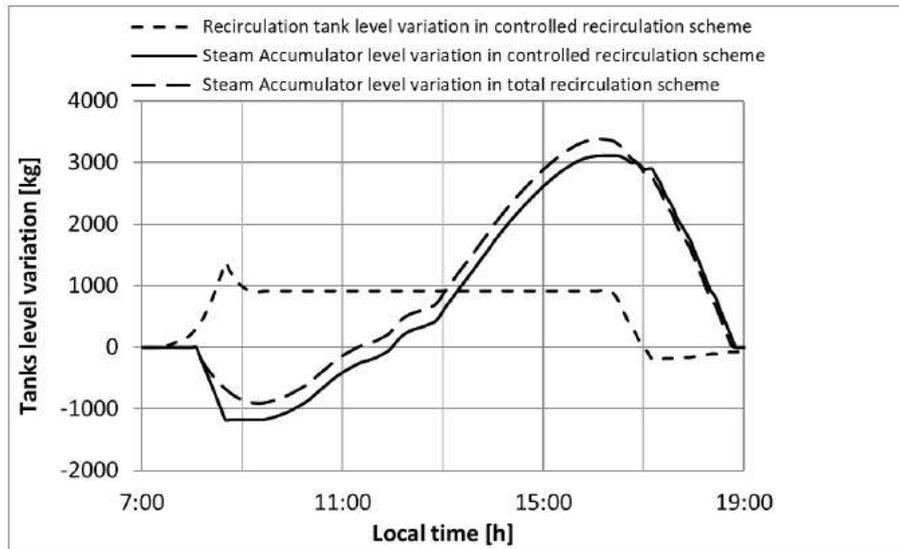


Figure 13. Cumulative volume of the tanks in both controlled and immediate recirculation operations, for the design DNI of 400 W/m^2 on January 1st, 2017

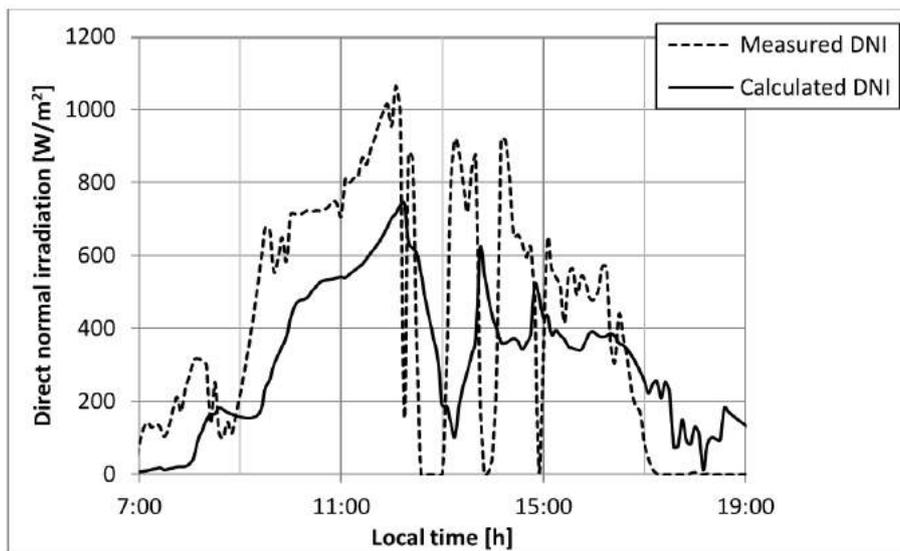


Figure 14. DNI calculated as the average of the time intervals inside the flow residence time, for the design DNI of 400 W/m^2 on January 2nd, 2017

Table 2. Tanks volumes and discharge durations calculated for each configuration

Day	Operation scheme	DNI_{dmax} [W/m^2]	Total duration [h]	High pressure duration [h]	Steam accum. volume [ℓ]	Rec. tank volume [ℓ]
Jan 1st	[1]	300	14.83	9.25	9,534.80	1,019.26
Jan 1st	[2]	300	14.50	7.50	9,537.75	-
Jan 1st	[1]	400	10.75	8.08	5,356.72	1,966.75
Jan 1st	[2]	400	10.75	6.67	5,361.56	-
Jan 2nd	[1]	300	12.50	7.75	7,264.99	2,577.49
Jan 2nd	[2]	300	12.67	6.58	7,081.07	-
Jan 2nd	[1]	400	6.50	6.83	3,780.00	3,772.99
Jan 2nd	[2]	400	6.50	3.50	3,288.78	-

[1] means immediate recirculation and [2] means controlled recirculation

high pressure operation duration is bigger. The discharge from the collectors is in high pressure, while the discharge from the steam accumulator is in lower pressure, and the controlled recirculation scheme power took more advantage of the high pressure liquid flowing inside the collectors.

With a bigger variability day like the second simulated, the recirculation tank charge was bigger in the beginning of the day, making the estimate for the recirculation tank volume bigger. In contrast, high DNI values were not frequent, and the steam accumulator tanks estimated volumes for both operation schemes were smaller than the values from the previous day. It is noted, as well, that, as the second day had intermediate DNI values with a higher frequency than the first day, the recirculation mass flow control covered a bigger portion of the day, making the difference between the accumulators volumes estimates for the two schemes also bigger.

5. CONCLUSION

DSG plants were discussed and an imminent problem of DSG using PTC as receivers was enlightened. Different from plants applying other receivers, the only commercial DSG plant with parabolic troughs does not use steam accumulators, but only a hot water tank, working as steam separator and damping system.

The simulation of an evaporation line connected to a superheating line varying parameters explained the plant behaviour and how it can be harnessed to design a constant steam generation plant. The simulation of a selected day of operation showed a way to size the tanks. It is noticeable the potential the DSG has over other technologies because of its simplicity, and how this potential can be increased if the power delivery can be reliably guaranteed.

The simulation of a summer day with low irradiation variability showed the pros and cons of the controlled and immediate recirculation schemes. The controlled recirculation increases the operation time at high pressure, at the cost of a greater investment. The immediate recirculation is preferable because of its control simplicity but it operates less time at the high pressure promoted by the collectors.

The simulation of a second summer day with more variable DNI values showed how the tanks volumes estimates varied. So as to give good estimates for the tanks, all the available measured data or a selected range of different days can be analyzed. The wider the range of days to operate ruled by the scheme presented, the bigger are going to be the volumes estimates, and varying the $DNI_{dmax} - DNI_{dmin}$ interval according to weather forecasts makes possible that the operation be applied to all days over the year.

6. ACRONYMS

CSP - Concentrated Solar Power
DNI - Direct Normal Irradiation
DSG - Direct Steam Generation
HTF - Heat Transfer Fluid
ISG - Indirect Steam Generation
LFR - Linear Fresnel Reflector
PTC - Parabolic Trough Collector
ST - Solar Tower
TES - Thermal Energy Storage

7. ACKNOWLEDGEMENTS

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