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ScienceDirect

Energy Procedia 69 (2015) 328 – 339

Energy Procedia

International Conference on Concentrating Solar Power and Chemical Energy Systems, SolarPACES 2014

Performance of direct steam generator solar receiver: laboratory vs real plant

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Abstract

The Levelized Cost Of Energy (LCOE) of a Concentrated Solar Power (CSP) plant strongly depends on the costs and efficiency of the solar field. A three-fold configuration has to be considered to optimize the chosen technology: Thermal Energy Storage (TES), Heat Transfer Fluid (HTF) and the concentration system technology.

Direct Steam Generation (DSG) represents a realistic alternative to the existing HTF solutions (molten salt or diathermic oil) as it uses water to feed the plant and get steam to be potentially directly injected in the steam turbine.

When applied to parabolic trough, the whole plant is undergoing a sequence of technological new problems [1] presently under further investigation within the CSP community, as for instance dedicated innovative thermal energy storage systems [2]; the equilibrium between costs and efficiency is yet to have been exhaustively defined and leaves therefore large room for investigation and research.

This paper will be dealing with the dedicated efforts provided by Archimede Solar Energy to its DSG solar receiver (HCEDSG-12), presenting the solution chosen to get rid of the extremely hard operating conditions. Results obtained from half a year-long real plant investigation will be discussed, demonstrating the technical feasibility of this intriguing technology.

Peer review by the scientific conference committee of SolarPACES 2014 under responsibility of PSE AG

Keywords: DSG; Parabolic Trough; Linear Fresnel; Solar Receiver.

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Peer review by the scientific conference committee of SolarPACES 2014 under responsibility of PSE AG
doi:10.1016/j.egypro.2015.03.037

1. Introduction

Solar radiation provides the Earth with a huge source of energy and therefore a feasible and "clean" alternative to fossil fuels. The exploitation of solar energy in wide extended plants with large dispatchability of energy leads to technological developments among which CSP (Concentrated Solar Power) represents one of the most known, broadly distributed and mature technologies; solar plant, power block and, most important, energy storage have been subject of intense investigations and large improvements over the last years.

Within CSP applications, linear focusing systems are competing with tower technology in terms of costs, benefits and efficiency. An illustration of Parabolic Trough and Linear Fresnel system is provided in Fig. 1:

Fig. 1. Line focusing systems: Parabolic Trough (left) and Linear Fresnel (right).

The mirrors characterizing the linear focusing system concentrate the solar rays towards a focal line, where a row of solar receivers are placed. Fig. 2 provides a pictorial illustration of a solar receiver:

Fig. 2: solar receiver and its drawing (right) with focus on the glass envelop and the internal spectrally selective coated stainless steel pipe.

The solar receiver is designed to absorb the concentrated radiation and transfer it to a fluid flowing through the pipes, providing hence a medium at high temperature at the field outlet. Finally, thermal energy is transformed into electrical energy by mean of an auxiliary heat exchanger, a steam generator and a steam turbine.

A dedicated spectral selective coating is deposited on the stainless steel pipe in order to increase the optical efficiency of the receiver whose valuable parameters are absorptance and emittance. A coaxial glass envelope (join to the steel pipe via glass-to-metal seals and bellows) is devoted to maintain a designed vacuum pressure in order to reduce thermal losses to radiative phenomena only: to this aim, a getter alloy is also assembled in order to adsorb and absorb the outgassed chemicals over the whole expected receiver lifetime, the gases being the source of potential drop of the designed vacuum.

As for the Heat Transfer Fluid, the present dominant technology adopts diathermic oil which however has several drawback affecting:

- Maintenance: being a flammable medium, precaution and operation have to undergo strict precautions;
- Safety: being a toxic medium, it is surely not an environmental friendly solution;
- Efficiency: oil molecule limits the achievable maximum temperature to be Tmax=400°C, which leads to a lower efficiency in the thermodynamic cycle for steam production;

- Technology: oil is not a good HTF for Thermal Energy Storage, hence a heat exchanger needs to be enclosed in the plant. Moreover, the oil molecule deterioration in temperature is producing a pretty large amount of hydrogen which, among other properties, is characterized by a significant ability to permeate through the stainless steel and hence deface the vacuum.

A particular emphasis should be given to the consequences due to the last point: as the hydrogen produced by the oil molecule breaking up can appreciably permeate through the stainless steel, the solar receiver annulus can similarly loose its ultimate vacuum pressure. Additionally, being a very good thermal conductor, a H_2-full annulus will be subject to high thermal losses. Moreover, hydrogen is also not a fully getterable element, as it is characterized by an equilibrium which yields this element to be not permanently stacked into the getter bulk.

An alternative Heat Transfer Fluids is molten salt, which has been proven to provide several advantages both in parabolic trough plant efficiency (e.g: Archimede Solar Energy's demonstrative plants, see ref. [4], and the 5MWe plant of Priolo Gargallo in Italy, see ref. [5]) as well as in maintenance and operation (as for the experience gained by central tower system, as Gemasolar in Spain, see refs. [6] and [7]).

A further HTF is water which leads to the technology known as Direct Steam Generation, DSG, and presents a series of advantages to be potentially exploited which could overcome the present day difficulties.

Water allows to achieve a very high temperature T_{max}=550°C however at a pretty high pressure due to the its low thermal capacity. Moreover DSG permits potentially to directly feed the turbine, avoiding hence the insertion of a heat exchanger and increasing consequently the efficiency of the plant, as depicted in the "best scenario" illustrate in Fig.3 (see for instance [3]):

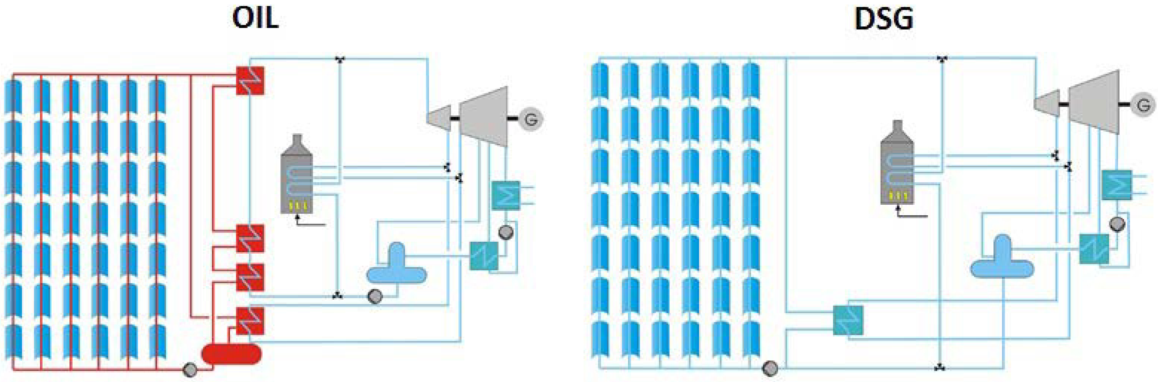


Fig. 3: comparison of a solar plant design for oil- (left) and DSG- (right) technology.

One of the disadvantages of DSG to present knowledge is related to the Thermal Energy Storage, TES: market available TES systems are presently adopting molten salt as the storage medium, limiting the potentiality of DSG (necessity of a heat exchanger and imposing a minimum temperature above 240°C, the solidification temperature for binary mixture molten salts). New TES technological developments dedicated to DSG will represent a breakthrough as these could increase the plant efficiency, avoid the insertion of the heat exchanger and permit to capitalize the very low temperature to be maintained during nighttime, just above the water freezing point.

A DSG parabolic trough plant include in its linear extension an interruption structure where pure steam is extracted by separating it from water in biphasic state (high pressure but medium temperature): this apparent constraint reveals actually to be an opportunity as it leaves choice to divide the field into an Evaporator and a Superheated block. This freedom turns out to be of major profit both for the design of the solar plant (unequal ground consumption for the two blocks) as well as for the devoted optimization of components in each block.

The poor thermal capacity of water drives however the design of the plant to be working with pretty high pressures, of the order or P_{max} = O(100) bar, this characteristics affecting directly the whole piping and, obviously, the Heat Collector Element, HCE, as well.

In this article, the thermal properties of the dedicated solar receiver, also known as HCE, are discussed in terms of the efficiency comparison before and after an experimental run carried on in a R&D plant in south Spain, work done in collaboration with a partner company not disclosed due to confidential constraints.

Finally, as thicker receivers means higher expenses for the DSG to be feasible, a study of alternative stainless steel is presented in order to get an overview of the possible cost reduction of this intriguing technology.

The operation and maintenance issues related to these severe operative conditions are out of the scope of this paper; O&M are referred back to ref. [1] for a comprehensive description.

2. Design of the experiment

The collaboration stands out of a Spanish company with long experience within CSP and parabolic trough in particular and Archimede Solar Energy, ASE, the only manufacturer of HCE stable up to a temperature of 600°C in vacuum. This collaboration pinpoint its scope to demonstrate experimentally the feasibility of the DSG technology by mounting and operating the system in the solar plant located close to Seville in south Spain.

As anticipated before, DSG requires the insertion of a fluid phase separator, or, in other words, the necessity to divide the plant into two blocks: only for investigation purposes, the collaboration has agreed to design the plant out of 2 lines each of 100 meters length, in order to study the evaporation and the superheated steam phase. Related to the solar receivers, dedicated medium- and high- temperature Heat Collector Elements have been manufactured in order to optimize the performances of each line.

For what concerns the transfer fluid, water will be circulating through the pipes at high pressure achieving very high temperature, according to a scheme where in the evaporator solar field the HTF will be biphasic (being present both in a liquid and in a vapor state), while in the superheated block the HTF will be circulating only in one phase, namely steam. The change of the physical properties of the two phases has been studied and taken into account in terms of heat transfer coefficient in order to fine tune the different mass flows.

The operating conditions required by the DSG technology strongly affect the receiver manufacturing process. While the solar receiver production process can be optimized to achieve separately higher absorptivity in the evaporator line and lower emissivity in the superheated block, the HCE material choice is driven by the necessity to guarantee mechanical robustness at those very high operating pressures: noble stainless steel degrees (as for instance aisi316) have been initially preferred to withstand that pressure.

In practice, the thickness of the receiver increases dependently on the maximum operative pressure: according to ASME B31.1, the large working pressure results into a thicker tube (> 4.5 mm) which directly reflects into an effective cost increase of the technology (a dedicated investigation is discussed at the end of the next section).

ASE's receivers, also called HCEDSG, have been produced with the scope to maximize the performances of the two blocks: fine tuning the sputtering process, a dedicated optical properties matching the design of the solar field could have been obtained. This flexibility has to be acknowledged to Archimede Solar Energy's sputtering methods and the characteristic of its spectral selective coating, namely its stability at high temperature.

An overview of the solar receiver properties is summarized in the following Table 1:

Table 1. Properties characterizing the solar receiver divided for the two blocks: Evaporator and Superheated lines.

HCEDSG-12	Glass Properties			Spectral Selective Coating		
	AR-coated glass length [mm]	τ on coated glass [%]	τ uncoated glass [%]	α [%]	ε (T=400°C) [%]	ε (T=550°C) [%]
Evaporator	3922 ± 3	96.9 ± 0.2	91.8 ± 0.2	95.9 ± 0.25	8.3 ± 0.2	
Superheated	3900 ± 3	96.9 ± 0.2	91.8 ± 0.2	95.2 ± 0.25	7.3 ± 0.2	10.3 ± 0.3

The optical parameters reported above has been calculated from reflectance measurements by mean of a Perkin-Elmer spectrophotometer equipped with an 150 mm integrated sphere

The most interesting investigation is however related to the high temperature line, namely the superheated steam block of receivers. This block is composed out of 24 HCE disposed as illustrated in the following Fig.4:

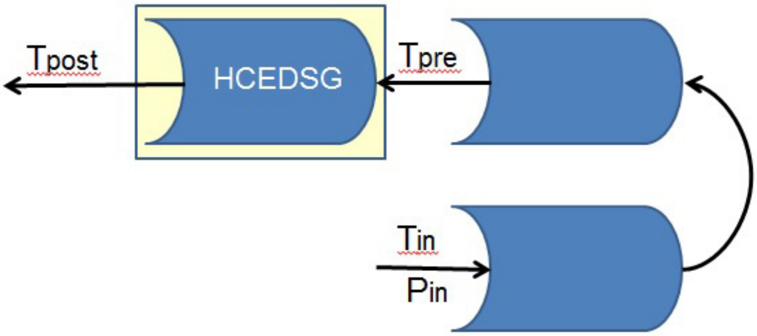


Fig. 4: placement of the superheated dedicated receivers along the superheated block.

The investigation has been carried on during the summer period, between May and September 2013, achieving an operation run of more than 500 hours. The irradiation reference peak has achieved a value of DNI ≥ 860 W/m^2 pretty constantly over the central summer period. The operative mass flow cannot be disclosed as for data protection of the Spanish partner owning the solar plant.

A number of thermocouples have been inserted to monitor the temperature behavior of the system during the expected 500 hours of operation; the HTF pressure has been varied in the range [60 ÷ 90] bars. Although the absolute value of the mass flow remains hidden, it is important to recall that its setting has remained constant to its reference value up to solely some testing where a variation of around 15% with respect to the central value has been imposed.

3. Measurements

The collaboration has obviously started with a careful characterization of the receiver performance in the laboratory of Archimede Solar Energy. One of the figures of merit of the thermal efficiency of solar receivers is the thermal loss at different stainless steel temperatures, as illustrated by the following Fig. 5

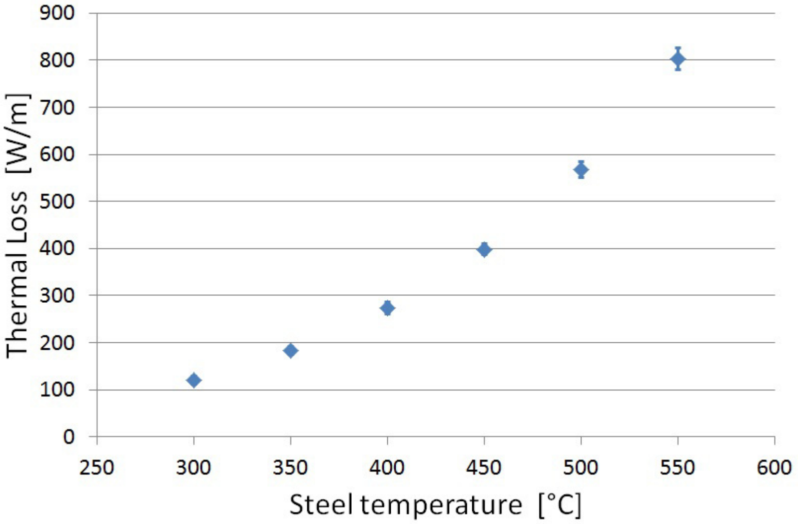


Fig. 5: Thermal losses as a function of the stainless steel temperature as measured in the laboratory before the outdoor exposure.

The data reported also show a tiny error bars which is to be traced back mainly to statistical fluctuations, as the solar receivers manufacturing has been carried on over several months[†] non-continuously.

The HCEs have then been mounted on the collectors on field and equipped with a dedicated external shield, the latter being designed in accordance with the latitude of the solar plant close to Seville and with the geometrical constraints of the existing collector: the scope of the external shield is to avoid the concentrated rays to hit the glass-to-metal seal.

Due to the experimental nature of the run and the sensible data protection, the global efficiency cannot be disclosed here. Moreover it should be noted that soon after the installation of the receivers, one HCE has undergone a glass envelope breaking due to an incorrect mounting of the external shield leaving that receiver exposed directly to air, see Fig. 6, representing hence a source of very high thermal losses

Fig. 6: the right receiver without the glass envelope, fully removed after the breaking event.

The evaluated global efficiency has obviously turn to be partially reduced; nonetheless it has been decided to not replace the receiver in order to allow ASE to carry on a specific very interesting analysis on that HCE, exposed for almost 4 months directly to air, while concentrated solar rays have heated up its temperature to [490 – 520]°C.

Adopting the notation illustrated in Fig. 4, a typical steady state has shown to be characterized by T_{pre}=450°C and T_{post}>550°C, as illustrated in the following Fig. 7:

[†] Moreover, measurements techniques have undergone an improvement procedure in order to get rid of the large quantity of receivers to be tested: a parallel measurement test bench has been developed at the expense of a slightly less accurate result reflecting hence into slightly larger error bars.

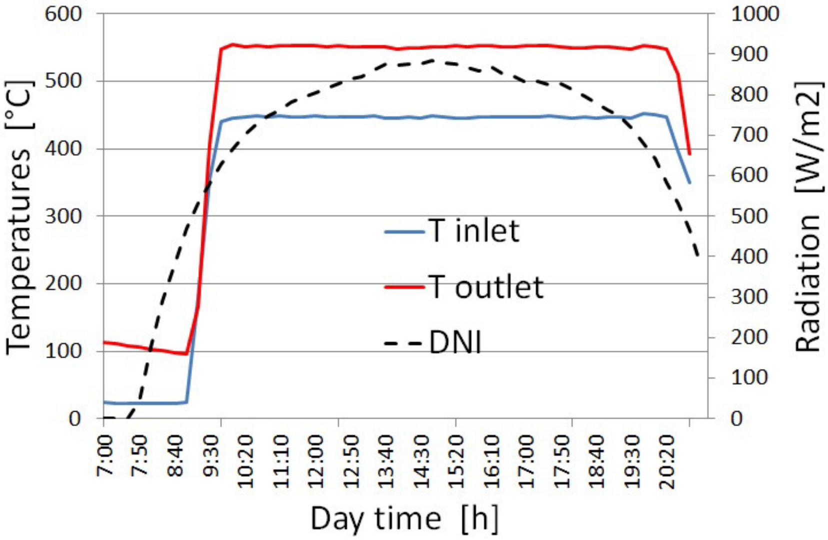
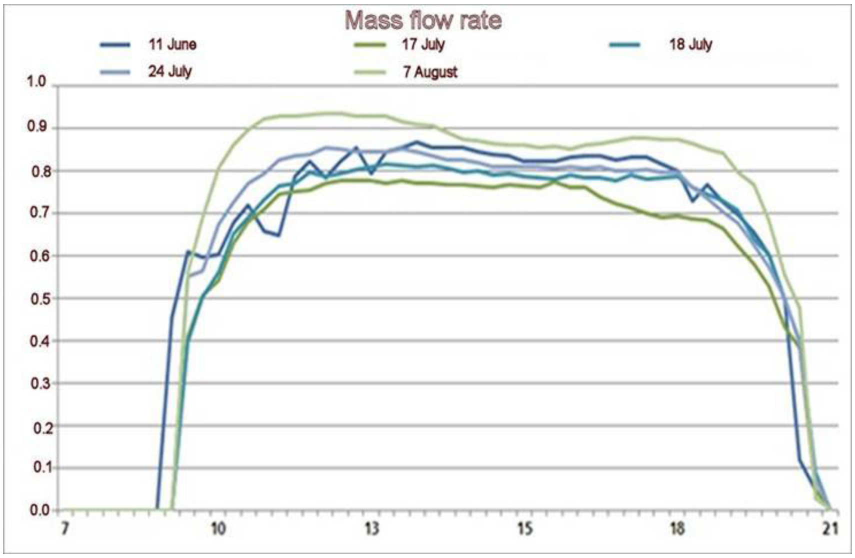


Fig. 7: Stability of the thermal properties of the superheated loop during steady state conditions.

The most interesting information for the evaluation of new technologies are related however to the transient states. The monitored data of our DSG experimental run are described in the subsequent figures and tables, to the extent that still allows for the sensible data to remain undisclosed. The following brief summary leads to an encouraging appeal.

The two plots of Fig. 8 below are both normalized to their reference value: the upper plot illustrates the stability of the mass flow over the day, for variation over a range of ±15% from the mass flow reference value. It is clearly visible that the only instability refers to June 11th , a very cloudy day. Even with this circumstances, the $\Delta T = T_{post} - T_{pre}$ behavior illustrated in the second plot indicates a very good stability over the whole day.



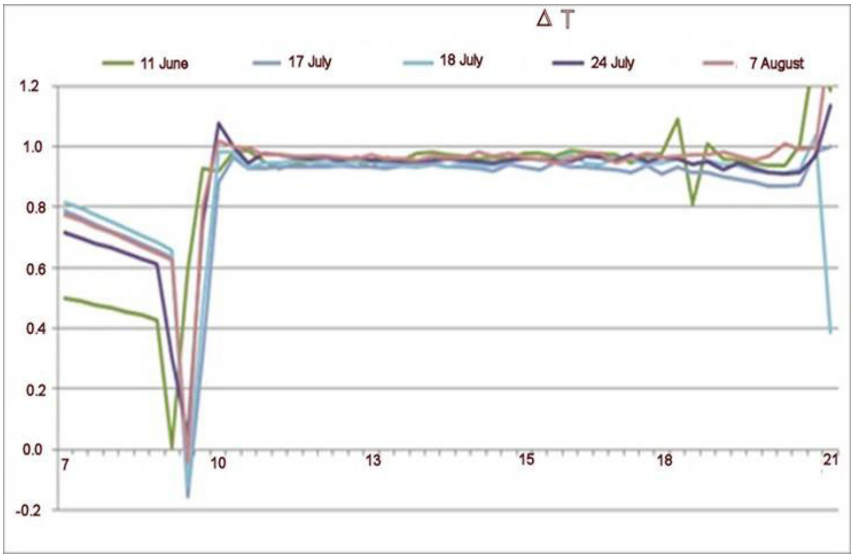
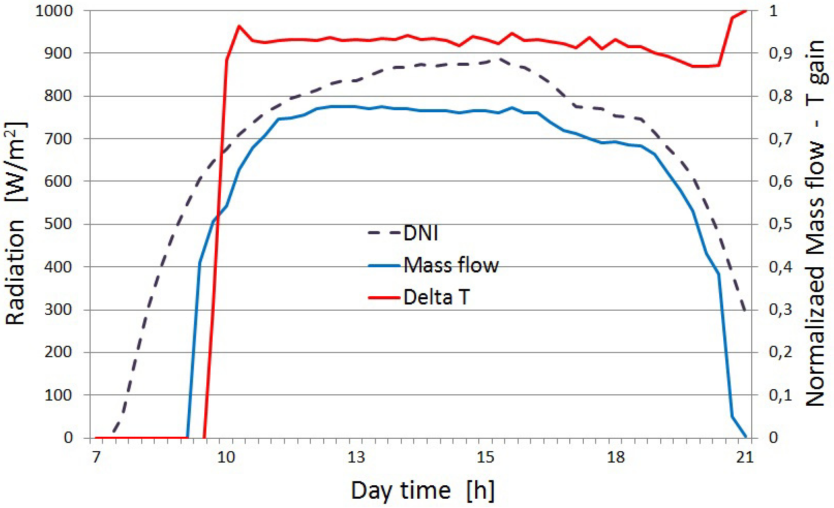


Fig. 8: Top: stability of the mass flow settings in a range close to its reference value. Bottom: the corresponding effects on the temperature increase between collector inlet and outlet.

Although the y-values are normalized, the following conclusions can be drawn: the upper plot shows the possibility to achieve a very steep ascendant curve in the transient state close to the sunrise, as depicted for instance by the data of August 7th ; the second plot provides with the HTF temperature increase between the collector inlet and outlet, $\Delta T = T_{post} - T_{pre}$: it can be doubtless concluded that it has been successfully obtained a constant ΔT in spite of mass flow variation even for cloudy mornings, as the curve related to June 11th demonstrates. The final remark concerns with the negative peak, which refers to the time lapse where the fluid is pre-heated while the collectors are still not focusing, yielding hence a higher inlet temperature with respect to the outlet temperature.

Another figure of merit for the evaluation of the efficiency of a solar plant operated with DSG technology is related to the run behavior in non-ideal conditions, as for instance during cloudy days.

Different meteorological conditions have been monitored and analyzed; Fig. 9 provides with a comparison of the effects on the DSG run efficiency (choosing ΔT as the valuable parameter) between a mid summer- and an early autumn- day



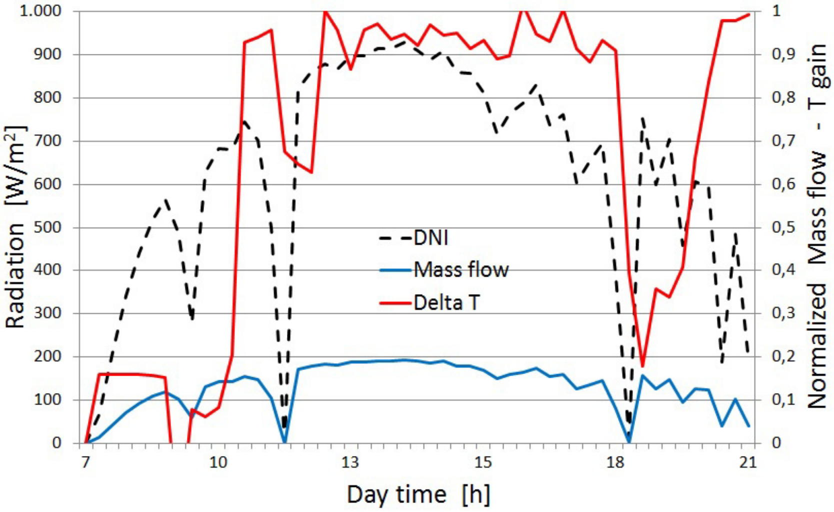


Fig. 9: the normalized temperature increase during the daily hours plotted as a function of the normalized mass flow (both on the right y-axis) and the DNI (left y-axis) during a typical summer day (top) and a cloudy day (bottom).

The comparison between such different configurations (full sunny vs cloudy rich days) has been possible by properly tuning the mass flow: for the autumn day, the latter has been lowered to about 20% of its nominal (summer) value in order to achieve the same maximum temperature at the loop outlet, namely T_{max}=550°C.

Finally, the most typical transient state is depicted in the following Table 2, in terms of the most important parameter characterizing the run in a solar plant. The transient period has been subdivided into

- Pre-heating phase of 30 minutes (between 8:30 and 9:00 in the previous pictures);
- Steady condition achievement phase of more 30 minutes (between 9:00 and 9:30).

Absolute values and plots are not presented in order to accomplish with the confidentiality constraints requested by the research partner

Table 2. Parameter behavior of a typical transient state during summer time

Time	Pressure [bar]	DNI [W / m^2]	T_{in} [°C]	T_{pre} [°C]	T_{post} [°C]
0 min	P_0	570	$T_{in,0}$	$T_{pre,0}$	$T_{in,0}$
30 min	$P_0 + 20$	650	$T_{in,0} + 80$	$T_{pre,0} + 90$	$T_{post,0} + 90$
60 min	$P_0 + 40$	720	$T_{in,0} +100$	$T_{pre,0} +310$	$T_{post,0} +430$

It is important to remark that in the morning hours the DNI was still raising and far from its peak (> 860 W/m^2); the values presented in Table 2 refer to a run characterized by a mass flow reduced to about 75% of its reference value.

The achievement of the desired outcomes (i.e: designed maximum temperature at the collector outlet) in a relatively short time are extremely encouraging for the DSG technology and stimulates a longer run, spanning over a timeframe larger than one year focusing the attention especially on the seasonal transient states. Last but not least, a longer run could provide a cross check of the theoretical studies carried on to estimate the corrosion phenomena associated with the DSG technology.

Finally, the receivers have been dismounted and shipped back in order to undergo a thermal loss analysis in ASE’s laboratory, repeating exactly the same process and using the same equipment as those adopted for the measurements illustrated in Fig. 5. A comparison between receiver performances pre- and post- the experimental run has hence been possible: Fig. 10 illustrates the thermal loss behavior of those receivers which have undergone the preliminary test and the full run at the solar plant in Spain. The focus has been posed to those receivers which have experienced the most critical operating conditions (highest temperature) during the run of about 700 hours:

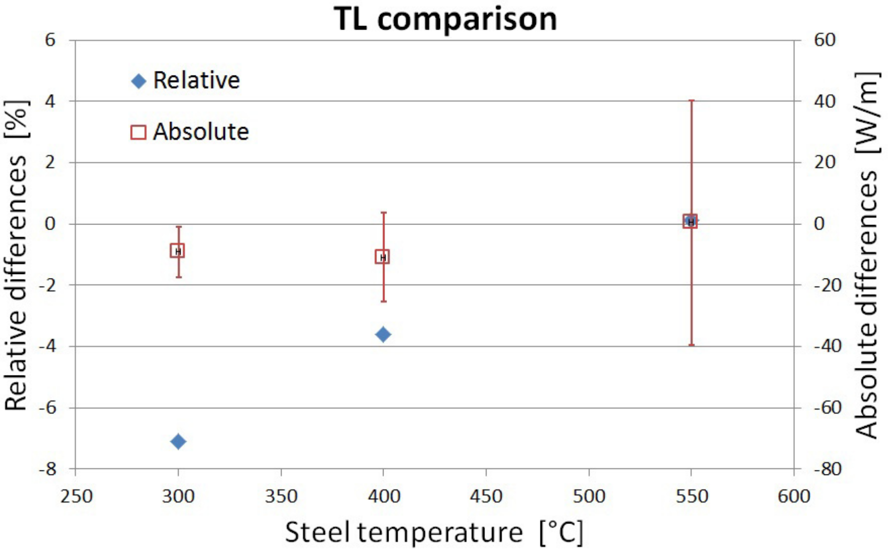


Fig. 10: Stability of the thermal loss of the HCE before and after the on-field run.

It can be clearly seen that the receivers do not change their thermal efficiency. For the sake of completeness, it should be stressed that the large error bars affecting the red squares are due to geometrical variation on the pipes: the returned receivers have indeed slightly lost their homogeneity in diameter during the mounting/dismounting operations, not allowing a perfect matching with the laboratory equipment and hence largely affecting the ASE’s measuring facility

Nevertheless, it can be stated that within the uncertainties related to the measurement technique (systematic and statistical), even the most stressed DSG dedicated solar receivers have maintained pretty stable thermal performances over the half a year on-field experimental run.

As a final step towards a complete evaluation of the DSG technology a dedicated analysis has been conducted about the costs and expenses related to the receivers optimized for this technology. The request to increase the fluid working pressure to values of the order of O(100) bars are driven by the poor thermal capacity of water. However, working with such a high pressure reflects into thicker piping and finally into higher costs of solar receivers, which is in contrast with the continuously demand of the CSP community to seek for cost reduction of the whole solar plant.

The competences of the author can just be restricted to the solar receivers and therefore an investigation of the expenses related to the HCE has been carried on and are presented into the following Table 3, which illustrates the percentage cost distribution of the HCEDSG-12

Table 3. Cost splitting of the DSG solar receiver

	Raw Materials	Consumable	Others
Impact %	42.9%	7.7%	49.4%

which clearly illustrates the huge impact due to the raw material expenses. Focusing into this latter macro-area, the following Table 4 describes the cost impact of the main components of the solar receiver

Table 4. Cost impact of the main components within the category or raw materials

	Stainless Steel	Bellow and Getter	Glass
contribution %	[59 ÷ 84]%	14%	9%

indicating undoubtedly where to concentrate the efforts for a cost reduction. The square brackets for stainless steel express the fluctuations of the costs as a consequence of its very strong dependence on stainless steel grade, thickness and, last but absolutely not least, on the steel supplier.

It should be noted that for the optical properties presented in Table 1 to be guaranteed, the supplied steel pipe has to fulfil very strict tolerances requirements, both in terms of geometry as well as of cleaning and surface roughness.

A market investigation has thus been started to identify needs, suppliers, technical requirements, commodity and finally costs: the outcome is a complex 4-dimensional matrix summarized here only by mean of its criteria representing the most impacting source of expenses:

- DSG plant design: T_{max}=550°C, maximum pressure up to 125 bar;
- Manufacturing technology: Electrowelded versus Seamless piping;
- Supply chain: market commodity and achievable roughness requirements;
- Present producer: costs and quality as declared from European- and from Far East- supplier.

4. Conclusions

The investigation of the DSG technology has turn to be successful for what concerns the behavior and performances of the solar receivers, although the global efficiency has been hidden to accomplish with the collaboration constraints. This conclusion is even more valid when considering the damaged receiver which has been working for more than 4 months without glass envelope and hence with higher thermal losses; this HCE permits to gain some additional information about the phenomenon affecting the spectrally selective coating due to its instability when exposed to air at very high temperature (≥ 500°C).

The DSG collaboration has run the R&D solar plant for more than 500 hours at a maximum pressure of 90 bars and achieving the designed temperature of 560°C at the collector outlet. It has been shown that steady states are easily reached and maintained for different meteorological conditions (summer and autumn); transient states analysis could have not be fully disclosed, but the described outcomes provide an indication to obtain a steep ascendant temperature raise with an affordable mass flow fine tuning. Moreover, it has been demonstrated that after a tunable pre-heating phase, the final steady state is achieved after just another 30 minutes.

For what concern the solar receiver performances, it has been proven that its thermal efficiency did not change by comparing the thermal losses before- and after- the run over more than 500 hours of real operative conditions.

These positive results confirm the suitability of Archimede Solar Energy's dedicated solar receivers HCEDSG-12 to be operated into a direct steam generation technology plant.

For the DSG to become a feasible technology within parabolic trough CSP plant, still some general aspects have to be optimized: while it sounds obvious to preserve the high thermodynamic efficiency provided by solar plant operating at very high (P,T) conditions, it would be fruitful to develop a new plant design to reduce Operation and Maintenance, but more than others, it reveals as a must to design and develop an efficient and cost-effective Thermal Energy Storage.

Within the solar field, the design of the plant requires high pressures, thus a thicker piping and hence an appreciable increase of costs: this economic issue represents one of the drawback affecting the DSG technology. A detailed analysis of the cost composition of the solar receiver led us to indicate the guidelines to follow in order to yield a cost-appealing DSG receiver, preserving the necessary technical specification requirements.

As a forthcoming improvements, beside the compulsory and desirable cost reduction, it is worth to recall the opportunity provided by the DSG technology, namely the freedom to split the DSG solar plant into an evaporator and a superheated block, allowing herewith a further optimization of the HCE properties in terms of its optical parameters (α,ε), of optimized bellows and of active collection area.

Acknowledgements

The author would like to thank S. Donnola for the continuous fruitful discussions and the ideas shared to optimise some important details (external shield, among others) for the run to be successful.

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