Analysis and potential of once-through steam generators in line focus systems – Final results of the DUKE project

Jan Fabian Feldhoff, Tobias Hirsch, Robert Pitz-Paal, and Loreto Valenzuela

Citation: AIP Conference Proceedings **1734**, 100006 (2016); doi: 10.1063/1.4949194
View online: http://dx.doi.org/10.1063/1.4949194
View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1734?ver=pdfcov
Published by the AIP Publishing

Analysis and Potential of Once-through Steam Generators in Line Focus Systems – Final Results of the DUKE Project

Jan Fabian Feldhoff[1, a)], Tobias Hirsch[1], Robert Pitz-Paal[2], Loreto Valenzuela[3]

[1]*DLR-Institute of Solar Research, Dept. of Line Focus Systems, Wankelstr. 5, 70563 Stuttgart, Germany.*
[2]*DLR-Institute of Solar Research, Co-Director, Linder Höhe, 51147 Cologne, Germany.*
[3]*CIEMAT-PSA, Solar Concentrating Systems Unit, Plataforma Solar de Almería, 04200 Tabernas, Almería, Spain.*

[a)]Corresponding author: jan.feldhoff@dlr.de, phone: +49 711 6862-362.

Abstract. The direct steam generation in line focus systems such as parabolic troughs and linear Fresnel collectors is one option for providing 'solar steam' or heat. Commercial power plants use the recirculation concept, in which the steam generation is separated from the superheating by a steam drum. This paper analyzes the once-through mode as an advanced solar field concept. It summarizes the results of the DUKE project on loop design, a new temperature control strategy, thermo-mechanical stress analysis, and an overall cost analysis. Experimental results of the temperature control concept at the DISS test facility at Plataforma Solar de Almería are presented.

INTRODUCTION

Direct steam generation (DSG) is a promising option to reduce the levelized cost of thermal energy (LCOE) in line focus systems, such as parabolic troughs or linear Fresnel collectors. DSG plants are already in commercial operation in Spain [1] and Thailand [2]. Those plants apply the recirculation concept, which foresees a separation of evaporation and superheating loops by a central stream drum. The research project DUKE (Durchlaufkonzept – Entwicklung und Erprobung) dealt with the detailed analysis of the once-through mode (OTM). This concept is also referred to as solar once-through steam generator. Its configuration foresees only one loop for preheating, evaporation and superheating of the water/steam. By adding parallel loops, the same easy scalability as for thermal oil or molten salt loops is achieved, which significantly simplifies the design procedure of a DSG solar field.

Two main drawbacks had been identified by the DISS project [3] that so far limited the application of the OTM. The endpoint of evaporation (EPE) is not fixed, but fluctuates within the loop. This was thought to cause severe thermo-mechanical stress of the receivers [4], which can reduce the life time of the components. Second, outlet temperature control was successful on days with stable direct normal irradiance (DNI) conditions, but was deviating significantly already with small passing clouds [5]. Within the DUKE project, a new control concept has been developed and was successfully demonstrated at the DISS test facility at the Plataforma Solar de Almería in Spain. Some experimental results are included in the paper. After the detailed analysis of the mentioned challenges, a significant cost reduction potential of a once-through configuration is found compared to the recirculation mode. This paper provides an overview on the most important results.

ONCE-THROUGH LOOP DESIGN

The main task of the loop design is to find a suitable loop length in accordance with all major boundary conditions. One of these boundary conditions is the geometry of the collector and receiver. A scaled EuroTrough collector with 150 m length and 5.78 m aperture width as well as Schott PTR-70-DSG receivers with 70 mm outer diameter and 58.8 mm inner diameter are assumed in the following. The live steam conditions and the inlet temperature to the solar field are usually given as boundary condition from the steam turbine or power plant. For

SolarPACES 2015
AIP Conf. Proc. 1734, 100006-1–100006-9; doi: 10.1063/1.4949194
Published by AIP Publishing. 978-0-7354-1386-3/$30.00

medium to high shares of superheating, one result of transient simulations is the recommendation to use two injections within each loop (Fig. 1). This aspect is explained in more detail in the section on temperature control below. Nevertheless, it is useful to introduce the reasons already here for design considerations. One injection is at the end of the evaporation section and is called evaporation injection (EVI). The other injection is called superheating injection (SHI) and is located close to the loop outlet. Together with the inlet control valve, these injections take care of a good balance between water/steam content in the loop and absorbed solar power. This balance is achieved best, if the steady-state temperature profile along the loop is maintained during transients. Exemplary temperature profiles are shown in Fig. 2 for a loop with 1500 m length (10 collectors in series) and outlet steam conditions of 500°C/110 bar. At nominal conditions, the inlet temperature is 260°C and the SHI reduces the steam temperature by 30 K, from about 460°C to about 430°C before the last collector. The EPE is shifted upstream with lower DNI level at constant inlet temperature. A reduced inlet temperature shifts the EPE downstream. As a result, the once-through loop can keep the EPE within the seventh collector for all steady-state conditions, while maintaining nearly the same thermodynamic conditions before the SHI. In consequence, keeping the temperature before the SHI (ϑ_1 in Fig. 1) constant can be chosen as an easy-to-implement control objective for all operating conditions. This is achieved by varying the inlet and the EVI mass flows. The SHI is dedicated to control the loop outlet temperature. One degree of freedom exists for the temperature profile: The temperature reduction by the SHI must be chosen, which at the same time fixes the location of the EPE, or vice versa.

Two additional degrees of freedom exist in the evaporation section, since the desired location and the mass flow share of the EVI can be chosen. On the one hand, the EVI should be close to the EPE and the superheating section for a fast transient control. On the other hand, the steam quality before the EVI should not be too high to avoid potential flow stratification or superheating before the EVI. A good trade-off is usually achieved when positioning the EVI at the location where a steam quality of about 0.75 to 0.85 appears. Experiments at the DISS facility showed no critical flow events even for steam qualities of about 0.9, which offers a small safety margin. The overall mass flow in the evaporation section before the EVI is determined by outlet steam conditions, SHI temperature drop and DNI level. Only the mass flow share of EVI and inlet mass flows can be chosen. Mass flow shares of 7 to 12 % showed good results during DISS experiments.

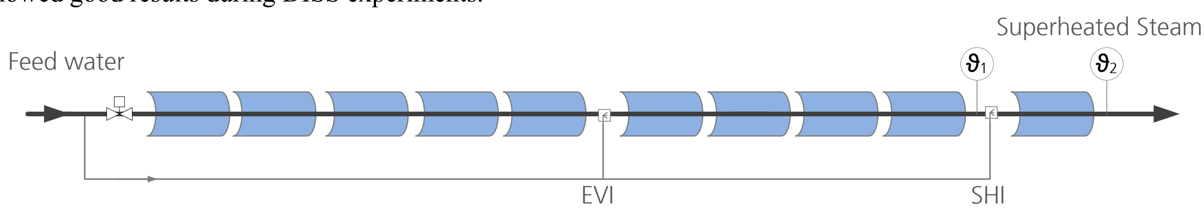


FIGURE 1. Schematic diagram of a once-through loop with inlet control valve, evaporation injection (EVI), superheating injection (SHI) and two measured steam temperatures.

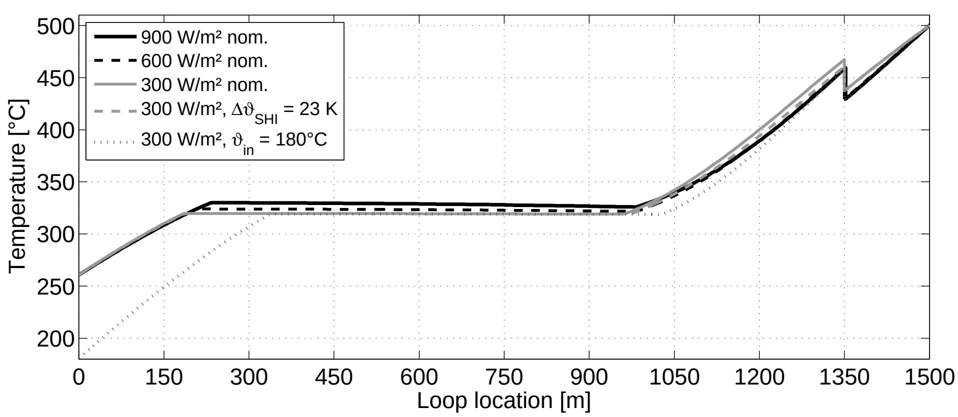


FIGURE 2. Temperature profiles for a loop with 1500 m/500°C; variations of irradiation level, temperature drop by the SHI and inlet temperature; nominal case with 30 K by SHI and 260°C inlet temperature.

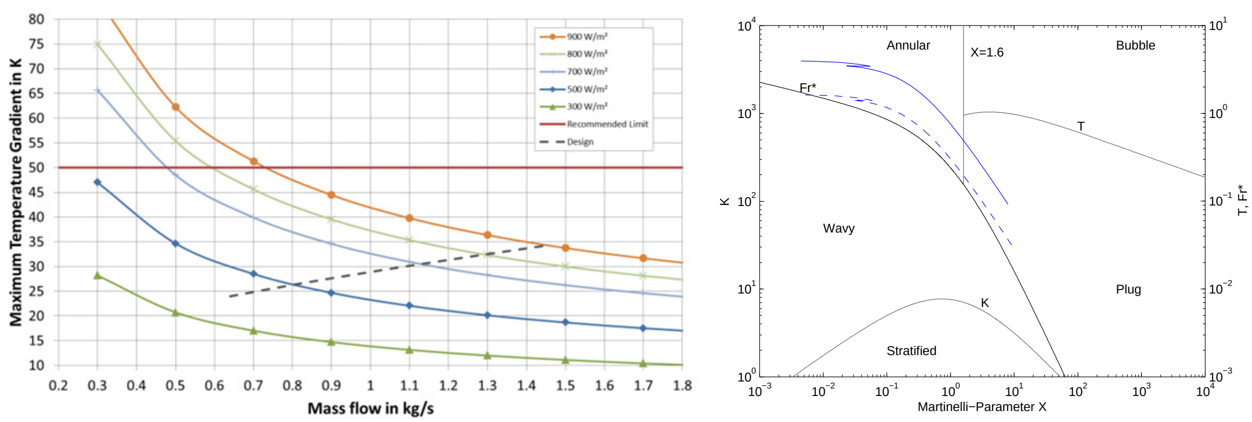
The general aspects on injections above do not reveal if it is a loop design for safe operation. Two analyses must be performed to assure secure operation at all conditions:

- The temperature gradients (thermal stress) within one receiver cross-section in the superheater section must remain below a safety limit.
- The flow regime in the evaporation section must assure a high and homogeneous heat transfer, which is predominantly achieved by annular flow.

Analyses on the superheating section have already been suggested e.g. in [6]. In the present paper, the Finite Element Method (FEM) model in ANSYS as presented in [7] is applied to the last receiver at the outlet of the DISS test loop for a steam temperature of 400°C. Figure 3a shows the resulting diagram of maximum cross-sectional temperature gradient dependent on mass flow. A typical flux distribution of a EuroTrough collector is used [7]. In general, a detailed stress analysis depending on the receiver material and wall thickness is advised to identify an appropriate limit of the temperature gradient. For simplicity, the 50 K limit as in [6] is shown in the figure, which already offers some safety margin in the DISS case. At 800 W/m² of effective irradiation (incident on the absorber tube), a minimum mass flow of 0.6 kg/s is needed to stay below the recommended limit. The design mass flow from the steady-state energy balance is 1.3 kg/s for the 1000 m/400°C DISS configuration and shows only about 33 K around the circumference. Thus, the design seems well suited. The same must be checked for the location upstream the SHI, since the steam mass flow is lower than at the outlet, while the temperature can already be high. The safety margin from the temperature gradient point of view increases with lower irradiation and steam temperature. Nevertheless, the complete range of the diagram should be analyzed in order to define acceptable off-design operating points during transients.

The second criterion considers the flow regime in the evaporation section. The flow pattern map of Taitel/Dukler [8] is applied to check, whether the flow is annular or wavy/stratified during various load conditions. Figure 3b shows two design curves of the 1000 m/400°C DISS loop at high and low irradiation level to be compared with the Fr* limit of the map. Both curves are above the map's limit such that annular flow can be expected. The applied map must be treated with care [9], but results from DISS experiments suggest that even close to the EPE no critical dry-out or stratification appears. The small safety margin thus seems to be sufficient. A safer design for a once-through loop would only be possible by increasing the loop length or decreasing the inner receiver diameter.

The paragraphs above showed that a safe design of a once-through loop is possible and the recirculation in the evaporation section is not required. This goal is achieved by a long loop length of about 1000 m for 400°C and 1500 m for 500°C at the outlet for the given geometries and boundary conditions. The resulting total pressure drop over the solar field is nevertheless lower or in the same order as in recirculation mode plants due to the omitted header piping related to the steam drum and a more efficient header alignment.



(a) (b)

FIGURE 3. (a) Temperature gradients within a receiver cross-section for the superheating section at a steam temperature of 400°C, simulated by FEM tool with typical EuroTrough heat flux density profile; (b) Taitel/Dukler flow pattern map with complete evaporation path design curves (Fr*) of DISS facility at 400°C/80 bar operation for 900 W/m² (-) and 300 W/m² (--).

TEMPERATURE CONTROL

The main advantage of the recirculation mode is its inherent thermal storage buffer provided by the steam drum. Short cloudy periods and the corresponding transients especially in the evaporation section are handled robustly and no significant flow disturbance appears at the solar field outlet [2]. The once-through loop does not comprise this buffer and clouds almost immediately have an effect on steam mass flow and outlet temperature.

All necessary controllers, e.g. for pressure control or valve openings, were suggested and implemented by Valenzuela [5] for control of the former 500 m DISS test facility. The main challenge is found to be outlet temperature control, i.e. variation of mass flow to achieve a constant outlet temperature of the collector loop. The first control strategy foresaw to regulate the mass flow at the inlet and at one injection before the last (50 m) collector of the loop. Proportional-integral (PI) controllers are used based on outlet temperature measurement and set point deviation. Feedforward action is applied for various influences such as injection water temperature, steam mass flow, DNI, and others. The concept showed good results for operation without clouds, but significant fluctuations during cloudy situations [5]. A different model predictive control (MPC) scheme was developed and tested for a linear Fresnel DSG plant [10]. However, only the inlet valve was controlled and even during clear sky days the outlet temperature showed high variations.

As a consequence, a new control concept for stabilizing the outlet temperature has been developed in this work. The main idea for the new control strategy was an easy-to-implement scheme for robust and efficient operation of first commercial plants, especially for parabolic trough solar fields. Each loop has an inlet valve control and, in the most robust configuration, two injections along the loop. A schematic diagram of the control is depicted in Fig. 4. The main idea is the splitting of the collector loop into two control loops. The SHI controller is in charge of outlet temperature control. The EVI controller shall keep the temperature before the SHI (ϑ_1) in a small bandwidth in order to have a good working range for the SHI. The inlet mass flow (IMF) controller is mainly based on feedforward action on the irradiation level. A feedback from steam temperature is possible, but is not recommended for cloudy situations. For simplicity of application, the injection mass flow controllers are based on standard PI controllers with feedforward. The time constants are derived based on ideas from Internal Model Control [11], which leads to robust controller performance. A predefined transition of the PI controller parameters, i.e. a gain scheduling scheme, is applied as well to adapt the controllers to the current irradiation/mass flow situation. This configuration allows for a fast and reliable rejection of disturbances.

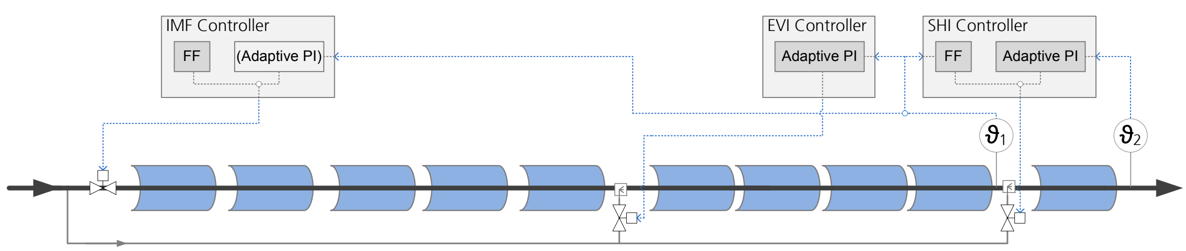


FIGURE 4. General scheme of controllers for temperature control of a once-through loop with two injections.

The following items further describe the most important system characteristics that need to be considered for control system design:

a) The water/steam loop cannot be modelled as an incompressible medium due to the high difference in density between inlet and outlet. Thus, a change in inlet mass flow has a significantly delayed effect on steam temperature (about 5 to 35 min). This fact is one of the main challenges and differences to thermal oil plants.

b) Cloud transients may appear only for a few minutes, such that a fast mass flow adaption is needed.

c) The system is highly distributed and DNI variations have very different effects depending on the location of the disturbance. In addition, it is not possible at the moment to provide a reliable measurement of DNI along all the collectors, but only at a few particular locations (e.g. one to five DNI measurements per power plant).

d) The system is unobservable in the evaporation section, i.e. the enthalpy cannot be measured. Only temperature measurements in the superheating section provide information about the system state.

e) The transfer characteristics significantly depend on the current mass flow, e.g. a lower mass flow leads to a slower temperature response. Thus, the manipulated variable (mass flows) influences the system behavior itself.

f) Energy disturbances at the inlet (inlet temperature or DNI) result in a non-minimum phase reaction with very strong undershoots. For example, a drop of DNI only in the first collector makes the steam temperature increase steeply at the loop outlet, before it quickly falls again and reaches a final value that is lower than the initial one. Details on this behavior are provided in [12].

g) The plant is non-linear, such that linear scaling is possible on gain and transfer function only in a very small range around an operating point. The non-linearity becomes more distinct with lower loads.

h) The system has various time-variant parameters, e.g. cleanliness, that cannot reliably be measured and that increase the overall uncertainty of the system response to a disturbance.

i) The temperature of the injected water (from feed water line) shows a significant influence on the mass flow effect of an injection, i.e. the gain of the injection transfer function changes.

j) The steam temperatures are very sensitive to mass flow variations. A change of about 1 % of inlet mass flow may lead to a change of about 10 to 20 K in outlet temperature. Thus, especially the IMF controller must be designed with care.

k) The numerical simulation of the complete loop is very difficult due to transient effects with very different time constants, especially in the evaporation section. The models are numerically stiff such that real-time simulation with accurate non-linear models is complex.

The mentioned system characteristics lead to a variety of changes compared to former control strategies:

- The inlet mass flow (IMF) is usually too slow for temperature control, such that a pure feedforward action on effective irradiation is recommended. In fact, temperature control on cloudy days would even worsen the disturbances. Pure IMF control without injections is not sufficient for disturbance rejection, unless a large amount of collector surface needs to be kept in stand-by/defocus in each loop. (derived from characteristics a, b, f and j)
- The IMF controller is based on feedforward on effective irradiation. It includes DNI and incidence angle modifier (IAM) effects. Even on days without clouds, the feedforward term is very important. It is not only based on the current DNI measurement (as in former concepts), but rather on a prediction of the clear sky DNI and IAM. The applied prediction period is the throughput time of the loop. (from a, e and j)
- The collector loop is divided into two control loops. The EVI controls the temperature before the SHI, while the SHI controls the outlet temperature. This configuration allows for a faster reaction during disturbances. For high superheating shares, the temperature ϑ_1 (see Fig. 4) may be further upstream than the SHI and closer to the EPE in order to have a faster controller. Nevertheless, temperature ϑ_1 must be in the superheating section. (from b and d)
- EVI and SHI work on a PI basis for simplicity of implementation. The two parameters of the PI controller, namely time constant and controller gain, are adapted as a function of the overall mass flow, i.e. inlet mass flow and injection mass flow(s). As the general behavior of a collector loop can be modelled well, a predefined function or table can be used. This procedure is called gain scheduling, with the mass flow being the scheduling variable. The effective irradiation may be added as scheduling variable for highly transient situations. (from e)
- The injection water temperature is used as an additional scheduling variable. It can compensate for strong variations of this temperature between start-up and nominal operation, which might be about 150 K at DISS facility. Former concepts recommended using the water temperature as feedforward variable. However, this ignores the effect on the process gain and can lead to strong fluctuations of the steam temperatures. Gain scheduling is recommended, while feedforward is then not needed. (from g and i)
- A non-linear and steady-state heat balance is used to derive a feedforward function from the temperature before the SHI to the variation of the SHI mass flow. If the temperature before the SHI increases, the mass flow of the SHI is also increased. This feedforward term is the most important one and the only feedforward term used for the injections in the basic control concept. (from g)
- A feedforward term for the enthalpy before the EVI is not used, since it cannot be measured. A dynamic feedforward function from inlet mass flow to EVI mass flow is useful, but has not been implemented for the basic control concept. (from a, c, d and j)

- The long time delays and multivariable interactions suggest the application of an MPC strategy. The practical implementation poses various challenges on such a strategy, especially good non-linear modelling in real time and a reliable, locally distributed DNI prediction. As a consequence, the basic control concept based on PI controllers is suggested for first commercial plants, but the MPC development shows significant potential to reduce temperature fluctuations and/or the number of injections. (from a, c, d, f, g, h, j and k)

The developed control concept has been validated by various experiments at the new DISS test facility at Plataforma Solar de Almería (PSA). Figure 5 shows an exemplary result for a period with small cirri and with heavier clouds provoking a DNI disturbance of up to -50 %. The reference temperature of 400°C, measured directly at the loop outlet, could be kept well within ±10 K, which enables smooth operation of a steam turbine. Only a longer drop in DNI at around 12:45 h causes a short temperature drop by -15 K to 385°C, which still does not cause any problems for standard steam turbines in a solar power plant. Only very strong cloud transients remain challenging for one loop, but are usually still acceptable when considering mixing and damping effects by various loops and the live steam header piping. More simulations and experiments have been carried out showing the same results. Thus, we can conclude that a reliable temperature control concept is now available for commercial application. Nevertheless, it must be noted that short periods of about 2 min or longer with completely shadowed solar field lead to high temperature fluctuations. If sites with many days of these events are considered, recirculation mode with its inherent buffer may remain the more robust choice.

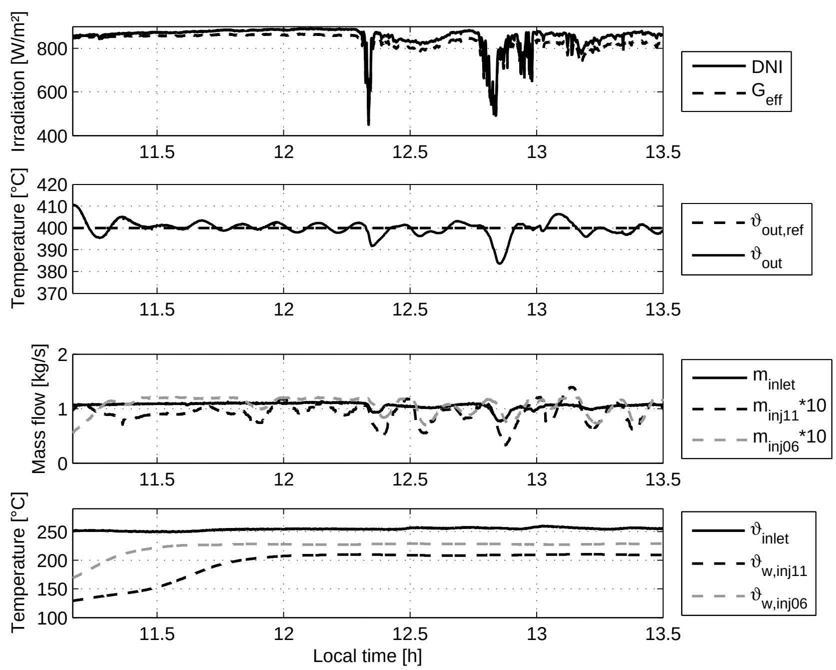


FIGURE 5. Control test for outlet temperature stabilization at 1000 m DISS test loop at PSA on June 24, 2015; new control concept with two active injections: EVI before collector 6 (650 m), SHI before collector 11 (850 m).

THERMAL STRESS ANALYSIS

There are two possibly critical locations in a once-through loop regarding stress. The first is the EPE, for which the exact flow regime and characteristics are hard to estimate. The second is at the end of the superheating section where the highest temperature of the steam causes the lowest heat transfer coefficient. Two analyses have been performed on these issues in the framework of the DUKE project. A short summary is provided by the following paragraphs. In [13], the ANSYS FEM tool as mentioned above is used to analyze the thermo-mechanical stress amplitudes. Temperature variations in the superheating section during normal/controlled operation do not show a significant impact on life time reduction of the receivers. Even during strong cloud transients, the thermal stress remains far below the fatigue stress limit [13].

Experiments at the DISS facility in once-through mode did not reveal high temperature gradients within a cross-section at the end of evaporation. Temperature gradients fluctuate between values for annular flow in the evaporation zone and values for superheating after the EPE. Thus, no critical dry-out was evident during experiments. A transient FEM analysis shows that resulting stress loads are also below the fatigue stress limit [13]. High stress amplitudes are only provoked by extreme fluid disturbances, e.g. a flooding of the hot superheating section (400°C) by saturated liquid (320°C) within a few seconds [13; 14]. These conditions are unlikely for normal operation and even their impact is still below the permanent fatigue strength. As a consequence, the life time of the receivers in a once-through loop does not seem to be significantly reduced by normal operation. The main life time reduction is expected to be caused by daily start-up and shut-down procedures, which must be considered for any solar field technology.

ECONOMIC COMPARISON WITH RECIRCULATION MODE

The economic comparison of DSG solar fields with once-through and recirculation is another important aspect for commercial projects. For comparison, nominal solar fields of about 244 MW_{th} have been designed for both recirculation mode (RM) and once-through mode (OTM). The nominal live steam parameters are 500°C/110 bar. The OTM field has 44 loops of 1500 meters each (380,160 m²). The RM field has 48x900 m evaporation loops and 52x450 m superheating loops (383,616 m²). The two layouts are shown in Fig. 6. The once-through configuration has longer loops and can offer a very efficient header piping design. The recirculation layout is a more compact version of the TSE-1 field in Thailand [2]. It is assumed that the other subfields are symmetrical and header piping can be used for two adjacent subfields together, e.g. the western piping of the OTM field is the same for its northern and southern subfield. The thermal inertia of the OTM field is much lower and the start-up temperature gradients can be chosen higher. In the RM field, the steam drum limits the start-up gradients. Furthermore, it is considered that the superheating section of the RM field cannot be focused until the evaporation section and steam drum provide a certain minimum mass flow. During normal operation, the pressure at the solar field outlet is fixed at 110 bar to allow for thermal storage charging. Only at low part loads, the pressure is decreased to a minimum of 80 bar, which allows for parallel operation with thermal storage discharge. The inlet temperature of the solar field is assumed constant for annual yield calculation. The comparison is limited to the solar field here, such that the levelized cost of thermal energy (LCOTE) is considered instead of electricity cost. The site of Tabernas, Spain, is chosen and data of 2013 is used with an annual sum of DNI of 2209 kWh/m². The following results summarize the comparison:

- Specific start-up energies, comparable to assumptions in [15], are estimated to be 0.52 kWh/m² for RM and 0.24 kWh/m² for OTM, which is about 54 % less.
- Header piping heat losses of the OTM are about 67 % less compared to RM.
- Overall pressure drop of the solar field is about 15 % or 4.5 bar less for OTM.
- The total solar field cost is calculated to be about 282 €/m² for RM and 233 €/m² for OTM, ca. 17 % less. (180 €/m² are considered for collector installation and are identical for both RM and OTM)
- The evaporation injection of the OTM accounts for about 6.4 €/m² including water piping and sensors, while the recirculation system requires about 12.7 €/m² without header piping.
- The annual useful energy yield is 448 GWh/year for OTM and about 4.4 % higher than RM.
- The nominal LCOTE reduction by OTM is about 22 %.

There are various uncertainties associated to the comparison. Figure 7 provides an impression on the main influences. If an 'ideal start-up' of RM field is assumed, i.e. all collectors focused at once at start-up, the energy yield of the RM increases and the potential LCOE reduction of OTM is reduced to about 19 %. If the start-up is not ideal, but start-up times are 'disturbed', i.e. 30 % longer, the OTM potential increases by about 1 %-point. If the same 'design pressure' is applied for both configurations, the OTM piping can be designed smaller and cheaper. This increases the potential by about 3.5 %-points to 25.5 %. The uncertainty of receiver life time can be exemplified by an arbitrary assumption of a 'receiver exchange' rate of two collectors per loop every five years, which is very conservative according to stress analysis. Even this assumption reduces the LCOTE potential of OTM only by 2 %-points to about 20 %. Another uncertainty is associated to operation at certain cloud patterns, such as a complete shadowing of the loop by clouds for more than about 3 min or high-frequency DNI fluctuations. It then depends on the solar field size and steam requirements, if such conditions may cause a break of turbine operation and a loss of energy. For the analyzed year 2013 at PSA, the overall energy content of potentially critical hours with high DNI variation sums up to about 16 %. This is again a very conservative estimate, as similar situations have already been handled in an acceptable manner at DISS facility and as RM might be unable to handle some events neither. Even if a complete energy loss of those challenging hours is assumed, the potential of OTM remains above 7 %. The overall economic comparison thus reveals a high potential of the OTM, which is still very promising, if worst case assumptions are considered.

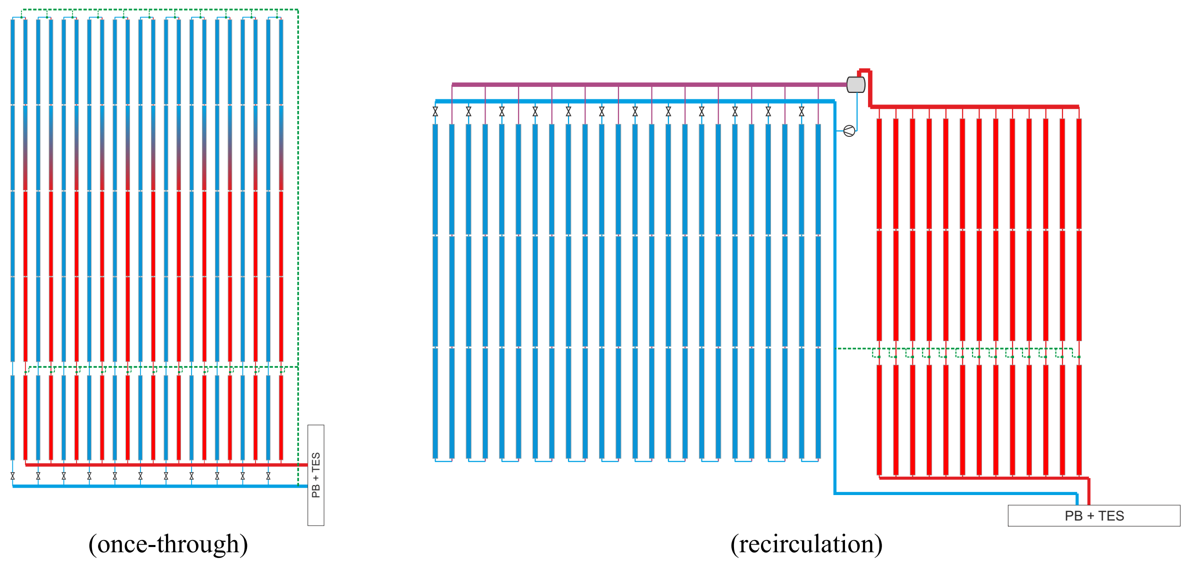


FIGURE 6. Schematic layouts of a north-west subfield for large-scale DSG solar fields with once-through mode and recirculation mode; (dotted) green lines indicate injection water piping; blue indicates evaporation, red indicates superheating.

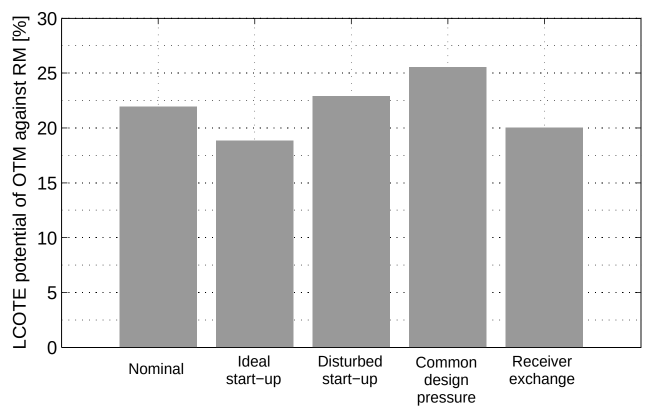


FIGURE 7. Influences on the potential of once-through mode (OTM) compared to recirculation mode (RM) for levelized cost of thermal energy (LCOTE) from solar field.

CONCLUSIONS

Solar once-through steam generators have been proven to be technically and economically feasible. A new control strategy for temperature stabilization has been developed and demonstrated at the DISS test facility at PSA. Very good results are achieved even for high DNI variations. Potentially critical situations in the superheating section and at the end of evaporation have been analyzed by steady-state and transient FEM simulations in order to estimate the impact of thermal cycling and corresponding thermo-mechanical stress. The results suggest that all disturbances cause stress amplitudes below the fatigue strength. Thus, the daily start-up and shut-down cycles remain the most important loads and no particular life time reduction is caused by the once-through configuration.

Detailed solar field design and cost estimation revealed a high economic potential of once-through mode compared to recirculation mode. There are high uncertainties within the economic assessment, since no commercial once-through plant exists yet. Nevertheless, the economic benefit is in the range of 7 to 25 % regarding the levelized cost of thermal energy from the solar field and the potential remains positive even when considering worst-case operation scenarios from cloud transients or fluctuations of the end of evaporation. DSG once-through solar fields are thus a reasonable choice for competitive solar steam generation, e.g. for solar hybrid plants or solar augmentation.

ACKNOWLEDGMENTS

The authors would like to thank the German Federal Ministry for Economic Affairs and Energy for the financial support given to the DUKE project under contract No. 0325293A. We also give special thanks to the operation and maintenance team of PSA's DISS test facility under supervision of Javier León, as well as to Rafael Gongora and Lothar Keller for their work in the control room during experiments.

REFERENCES

1. M. Mertins, E. Link, M. Tscheche and H. Leuckel, "Experiences of operation of 30 MW solar-thermal power station based on Fresnel collector technology," 18th SolarPACES Conference, Marrakech, Morocco, 2012.
2. D. Krüger, J. Krüger, Y. Pandian, B. O'Connell, et al., "Experiences with Direct Steam Generation at the Kanchanaburi Solar Thermal Power Plant," 18th SolarPACES Conference, Marrakech, Morocco, 2012.
3. E. Zarza, L. Valenzuela, J. León, K. Hennecke, M. Eck, et al., "Direct steam generation in parabolic troughs: Final results and conclusions of the DISS project," Energy, Vol. 29, 5-6, 2004, pp. 635-644.
4. W.-D. Steinmann and M. Eck, "Direct Solar Steam Generation in Parabolic Troughs: Thermal Stress due to Variations in Irradiation," 10th SolarPACES Symposium, Sydney, Australia, 2000.
5. L. Valenzuela, E. Zarza E., M. Berenguel and E. F. Camacho, "Direct steam generation in solar boilers - Using feedback to maintain conditions under uncontrollable solar radiation," IEEE Control Syst. Magazine, Vol. 24, 2, 2004, pp. 15-29.
6. M. Eck and W.-D. Steinmann, "Modelling and Design of Direct Solar Steam Generating Collector Fields," Journal of Solar Energy Engineering, Vol. 127, 2005, pp. 371-380.
7. M. Eck, J. F. Feldhoff and R. Uhlig, "Thermal Modelling and Simulation of Parabolic Trough Receiver Tubes," Proceedings of the ASME 2010 4th International Conference on Energy Sustainability, Phoenix, Arizona, USA, 2010.
8. Y. Taitel and A. E. Dukler, "A model for predicting flow regime transitions in horizontal and near horizontal gas-liquid flow," AIChE Journal, Vol. 22, 1, 1976, pp. 47-55.
9. T. Hirsch, J. F. Feldhoff, K. Hennecke and R. Pitz-Paal, "Advancements in the Field of Direct Steam Generation in Linear Solar Concentrators-A Review," Heat Transfer Engineering, Vol. 35, 3, 2013, pp. 258-271.
10. P. Tanner, K. Rasmussen, P. Johnson, A. Hoermann and W. Cheng, "Control of Solar Steam Generators," Proceedings of the ASME 2011 Power Conference, Denver, CO, USA, 2011, pp. 309-316.
11. M. Morari and E. Zafiriou, *Robust Process Control*, Prentice Hall, 1989.
12. J. F. Feldhoff, T. Hirsch, R. Pitz-Paal and L. Valenzuela, "Transient models and characteristics of once-through line focus Systems," Energy Procedia, Vol. 68, Proceedings of the 2014 SolarPACES Conference, 2015, pp. 626-637.
13. A. Rosselló Robert, "Charakterisierung der thermo-mechanischen Belastungen eines Parabolrinnen-Solarkraftwerks," Master thesis, DLR Stuttgart and TU Munich, 2015.
14. Materials Testing Institute University of Stuttgart, "Transiente Analyse Solarreceiver", Technical report No. 9022980000 for DLR Stuttgart, 2013.
15. T. Hirsch, J. F. Feldhoff and H. Schenk, "Start-Up Modeling for Annual CSP Yield Calculations," Journal of Solar Energy Engineering, Vol. 134, 3, 2012, pp. 031004-9.