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Experience of operating a solar parabolic trough direct steam generation power plant with superheating

Lisa Willwerth[a,*], Jan Fabian Feldhoff[b,1], Dirk Krüger[a], Lothar Keller[c], Martin Eickhoff[c], Joachim Krüger[d], Yuvaraj Pandian[d], Jörg Tiedemann[e], Manuel Succo[e], Abdallah Khenissi[b,2]

[a] German Aerospace Center, Linder Höhe, 51147 Köln, Germany
[b] German Aerospace Center, Wankelstrasse 5, 70563 Stuttgart, Germany
[c] German Aerospace Center, Plataforma Solar de Almería, Ctra. De Senés s/n, km 4, 04200 Tabernas, Spain
[d] Solarlite CSP Technology GmbH, Schloss Duckwitz, 17179 Duckwitz, Germany
[e] Tiede- & Niemann Ingenieurgesellschaft mbH, Harburger Schloßstraße 6-12, 21079 Hamburg, Germany

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ABSTRACT

TSE1 is the first solar thermal power plant operating in Southeast Asia. It was planned by Solarlite GmbH with support of Tiede- & Niemann GmbH, both German based. It is the first power plant with direct steam generation (DSG) concept and superheating in parabolic troughs. The solar field has a nominal power of 19 MW_{th} driving a 5 MW_{el} turbine by superheated steam at 30 bar and 330 °C. During 2010/2011 Solarlite built the solar field, while the later owner and operator Thai Solar Energy (TSE) from Bangkok built the power block, in Kanchanaburi, Thailand. TSE1 is being operated by TSE since January 2012 (Krüger et al., 2012).

This publication is based on a study within the KanDis project, funded by the German Federal Ministry for Economic Affairs and Energy, in which an extensive database of records of almost 500 sensors installed in the power plant (solar field and power block) has been investigated. The data have been provided by Solarlite with a time resolution of about 1 min.

Within the KanDis project, a stable operation could be demonstrated (Khenissi et al., 2015; Krüger et al., 2016). Even under the fluctuating irradiance conditions in the rainy season of Thailand, the turbine could be operated well and generate electricity. Evaluation of the operation data has helped to learn more about DSG behaviour. The TSE1 layout and the implemented control strategies were evaluated and strategies for improvement of TSE1 are suggested within this paper. From the experiences with the TSE1 power plant, conclusions could be drawn to improve the layout and control of future DSG plants.

1. Introduction

The process of pre-heating, evaporating and superheating water directly in the collector absorbers is called direct steam generation (DSG) (Hirsch et al., 2013). It is a promising option in solar thermal power plants to reduce costs and to increase the efficiency in comparison to conventional solar thermal power plants using oils as heat transfer fluid (Eck et al., 2008, Feldhoff et al., 2009). While common oils can only be used up to a temperature of 395 °C (new silicon-based oils promise temperatures up to 420 °C), water/steam can be superheated to higher temperatures. Upper temperatures of 500–550 °C seem reasonable with current line focus technologies. The steam parameters are not bound by the fluid, but by component design limitations such as receiver coating and material costs, as well as by heat losses and concentration factors.

DSG is a perfect match as fuel-saver for co-fired plants, e.g. with coal or biomass, but it can also be used for stand-alone plants. Integration to the live steam of high pressure turbines of existing plants is possible as well. DSG also can have the benefit of directly providing steam without additional heat exchangers, for example as process heat or for enhanced oil recovery. Furthermore, there is no risk of environmental pollution or extra investment costs due to environmental

Abbreviations: ANI, irradiance normal to aperture area; DNI, direct normal irradiance; CSP, concentrated solar power; DSG, direct steam generation; NMP, non-minimum phase; PI, proportional-integral controller; PSA, Plataforma Solar de Almería; SD, Steam Drum; TSE, Thai solar energy (company name, operator); TSE1, name of the appointed power plant in Kanchanaburi, Thailand

* Corresponding author.
E-mail address: lisa.willwerth@dlr.de (L. Willwerth).
[1] SWU Stadtwerke Ulm/Neu-Ulm GmbH, Karlstraße 1-3, 89073 Ulm, Germany.
[2] BP 71 Poste Hessi Jerbi, 4174 Zarzis, Tunisia.

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safety.

The feasibility of DSG in parabolic troughs has been proven within the European DISS project (Eck et al., 2003) in a single test loop at the Plataforma Solar de Almería (PSA). Within the Spanish-German REAL-DISS project, the experiences from the DISS project were used to implement a DSG collector in a conventional power plant in Carboneras, Spain (Eck et al., 2011). Components, especially the receiver tubes and flexible joints, were designed to withstand higher temperatures. Operation of the DSG solar field with temperatures up to 500 °C has been demonstrated successfully. Thereafter, the DISS loop was altered and operated to validate the benefits of the once-through concept within the German DUKE project (Feldhoff and Meyer-Grunefeld, 2016). Since 2009 DSG was commercially applied by the first linear Fresnel plant in Puerto Errado, Spain, PE1 and in 2011 a superheating collector was installed there to gain first experience. A stable operation was demonstrated (Morin et al., 2012). In 2012, DSG was commercially applied by the PE2 linear Fresnel plant and the TSE1 parabolic trough plant in Kanchanaburi, Thailand (Krüger et al., 2012; Khenissi et al., 2015). At PE2, the stable operation of parallel evaporation loops for a 30 MW_{el} DSG plant with saturated steam was demonstrated (Mertins et al., 2012). This paper presents the results of the KanDis project (Krüger et al., 2016), namely the operation of the 5 MW_{el} TSE1 plant with recirculation mode and superheating (see Fig. 1).

Fig. 1. Aerial view of TSE1, Kanchanaburi, Thailand.
Source: Solarlite.

The KanDis project aimed at investigating the operational behaviour of a commercial-sized DSG plant with evaporation and superheating in parallel loops, to estimate the stability of the process and to improve the layout, components and the control strategy for TSE1 and future DSG plants. Therefore operational data from 2012 to 2013 were analysed. This Paper offers unique and detailed insight into the experiences with control of a DSG evaporator and superheater field. It is not the aim of this paper to offer an analysis of the performance of the TSE1 plant over the two years period, which would not be representative, because it spans over the commissioning period and scientific test periods.

2. Description of the TSE1 power plant

The TSE1 solar field was built by Solarlite with the contribution of Tiede & Niemann in 2010 and 2011 whereas the power block was built by the owner Thai Solar Energy. Its design was described in Kruger et al. (2010). It consists of a solar evaporator and a solar superheater, both with SL4600 parabolic trough collectors. It is a DSG plant operating in recirculation mode. Water is preheated and partially evaporated within the evaporator. This two-phase flow of liquid and steam flows to the steam drum, where it is separated (Willwerth et al., 2016). The saturated steam moves on to the superheater field, where it is superheated. Therefore, the live steam mass flow depends on the evaporator field and the steam temperature depends on the superheater field. The superheated steam drives the turbine and is condensed. The condensate from the turbine, as well as the liquid phase from the steam drum, mix and re-enter the evaporator field. To optimise the flexibility of the 5 MW_{el} turbine, MAN adapted it to accept low partial load pressures during commissioning. The turbine is normally operated in fixed pressure mode where the control valves at the inlet of the turbine control the pressure in the solar field. The solar field output has to match or exceed the turbine swallowing capacity to reach the turbine's maximum rated power in normal operation. On the contrary, Sliding pressure control is achieved when the control valves at the turbine inlet are always fully open and the live steam pressure is therefore an indirect result of the mass flow delivered by the solar field. Fixed pressure control was adopted during regular operations and sliding pressure control was used during transient operation to prolong the turbine operation as long as possible.

Table 1
Technical parameters of the TSE1 plant.

Term	Value	Unit
Nominal thermal power P_{th}	19,5	MW
Nominal electrical power P_{el}	5	MW
Nominal live steam pressure	30	bar
Nominal live steam temperature	330	°C
SL4600 collector segment length	12	m
SL4600 collector aperture width	4,6	m
PTR70 receiver diameter	70	mm
Steam drum volume	25	m^3
Steam drum max pressure	43	bar

Some technical parameters of the TSE1 plant are collected in Table 1.

3. Data

A thorough analysis of the TSE1 operation was possible due to an extensive database of about 500 sensors from the solar field, from which data were transmitted about every minute from January 2012 to July 2013. The most interesting sensors are schematically drawn in Fig. 2. There are temperature measurements at the outlet of each single collector as well as in the steam drum and header lines. The tracking angle of each collector is also transmitted. Pressures are measured at the outlets of each evaporator loop, within the steam drum and in the header lines. Similarly, the water mass flows are measured at the inlet of each evaporation loop as well as at the outlet of the feed water pump. The steam mass flows are measured in each superheating loop as well as in the main steam line at the outlet of the solar field. The water content in the steam drum can be calculated by data from a level sensor. At the entry of the turbine, temperature, pressure and mass flow of the live steam are detected. The electrical power output measurement is only available from January 2012 to August 2012. Besides the sensors symbolised in the picture, there is also a weather station with sensors for direct normal irradiance (DNI), wind speed and wind direction. For the data analysis instead of DNI the irradiance normal to aperture area (ANI) is used, which is the DNI multiplied by the cosine of the incidence angle.

The uncertainty of each measurement is not elaborated upon here, since only qualitative conclusions shall be drawn.

4. Results from operation

Live steam output and the control of evaporator as well as superheater are evaluated in the following.

4.1. Live steam output

The TSE1 turbine has a nominal power of 5 MW_{el} at a nominal live steam pressure of 30 bar and a temperature of 330 °C. The TSE1 demonstrated that reaching and maintaining these live steam parameters