Renewable and Sustainable Energy Reviews 56 (2016) 611–630

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Control systems for direct steam generation in linear concentrating solar power plants – A review

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A R T I C L E I N F O

Article history:
Received 13 August 2015
Received in revised form
23 November 2015
Accepted 30 November 2015

Keywords:
Concentrating Solar Power
Line-focus
Direct steam generation
Control systems

A B S T R A C T

Concentrating Solar Power (CSP) plants generate renewable electricity using the conversion of solar direct normal irradiation into thermal energy, then into mechanical work and electricity through the use of a thermodynamic cycle. Among the several available technologies, Direct Steam Generation (DSG), in which steam is generated directly in the absorber tubes of the solar field, and then directly fed to the turbine or thermal storage, holds interesting advantages. However, the steam generation system shows a difficult dynamic behavior which constitutes a challenge for the control system design. It is mainly due to the conjunction of the natural transient condition of solar irradiation and the presence of two-phase flow in the absorber tubes. This paper reviews the control methods of the DSG systems used in linefocus CSP. The control systems are either proposed in literature, or actually applied in currently running plants or prototypes, although an extensive description is difficult to obtain in the case of the latter. The control systems are classified according to which DSG operation mode they refer to.

Contents

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http://dx.doi.org/10.1016/j.rser.2015.11.083
1364-0321/

1. Introduction

In the context of a world where primary energy consumption is constantly increasing, and where the climate change most optimistic scenario is now the limitation of the global average temperature rise above pre-industrial level to 2 °C, renewable electricity generation has a major role to play. Concentrated solar power (CSP) plants use the sun's direct normal irradiation to generate electricity using an intermediate conversion into thermal energy and a thermodynamic cycle. Current installed capacity worldwide is about 4 GWe [1], which is still a low figure as compared to photovoltaics. However, in its “hi-Ren” scenario, the International Energy Agency envisions a CSP contribution to the global electricity production of about 11% by 2050 [1]. It should be noted that this figure remains almost unchanged since the previous report [2], although CSP development was lower than expected in this intermediate period.

Among the several technologies used to collect heat in line-focus CSP technologies, the use of water/steam as both heat transfer fluid (HTF) and working thermodynamic cycle fluid constitutes the so-called direct steam generation technology (DSG). It offers several advantages compared to the synthetic oil that is used in most line-focus plants: the fluid is heated up to a higher temperature, and the overall configuration is simpler thanks to the absence of HTF piping and heat exchange components [3]. Although the potential of generating steam directly in the absorber tubes was identified in the early 80's [4], first studies to apply this technology to line-focus systems go back to the early 90's, with research effort regarding two-phase flow inside horizontal tubes [3–5,6]. Since then, numerous studies and research projects have been carried out, many of which surrounding the *DIrect Solar Steam* (DISS) experimental facility in Almeria [7]. A recent review by Hirsch et al. [8] gives a good overview of today's state of the art about direct steam generation. Recent studies about the potential of DSG compared to synthetic oil, considering the latest knowledge and technologies, are also available. The studies by Eck et al. [9] and Feldhoff et al. [10] show a potential reduction of the levelized electricity cost (LEC) up to 11%. They did not however include the use of thermal energy storage, which is a major asset of solar thermal electricity. This was done in a more recent study by Feldhoff et al. [11], in which it was shown that with the current state of the art on thermal storage, the LEC of a DSG plant could actually be higher than the one of an equivalent oil plant. Several leads are proposed to reduce the LEC, including the use of a specific DSG plant architecture, known as “once-through”. That architecture is however less applied today, mainly because it requires a more complex control structure.

The control system design of a CSP plant is critical to its proper operation since it has to handle the natural transient condition of solar irradiation, and it is even more important in the case of a DSG system in which the magnitude of the transient phenomenon is increased by the presence of two-phase flow inside the absorber tubes. The objective of this paper is to provide a state of the art of the control systems used for direct steam generation in line-focus CSP plants. The focus is mainly on the methods proposed in literature, and the actually applied systems as well, although information about operating power plants is difficult to obtain. In the first section of the paper, some general notions are given about DSG and how it is operated. The next three sections are dedicated to the control systems for each operation mode, and a last section focuses on operational experiences from the few currently running commercial plants. Advanced control being a vast and complex research field, some basic explanation is given each time a new control method is mentioned.

2. Direct steam generation in linear concentrating systems

2.1. Overall layout and physical considerations

As many of the conventional power plants, CSP plants use a thermodynamic steam Rankine cycle to generate work that drives an electricity generator. It therefore seems obvious that generating steam directly in the solar field reduces the complexity of the overall system. Fig. 1 below shows an ideal steam Rankine cycle (1a) and a simplified diagram of its application (1b) in a DSG plant (Fresnel collector is used for the schematic). Some details are also given for the involved thermodynamics processes. Numbered points on the figure refer to thermodynamic states between the described processes.

- **1-2-3-4: Isobaric heat transfer**. Feedwater is pre-heated to liquid saturation conditions either solely in the solar field or partly in a reheater and in the solar field. Water is then vaporized and steam is superheated in the solar field. Depending on the operation mode, vaporization and superheating take place in the same section, or separate sections. The process is ideally isobaric, but pressure drop actually takes place in the absorber tubes and the external piping.
- **4-5: Isentropic expansion**. Superheated steam decreases in enthalpy by being expanded in the turbine. The ideal process is isentropic, but entropy actually increases which leads to less energy transfer on the turbine blades. Depending on the power