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Impact of the operation of non-displaced feedwater heaters on the performance of Solar Aided Power Generation plants

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ABSTRACT

Solar Aided Power Generation is a technology in which low grade solar thermal energy is used to displace the high grade heat of the extraction steam in a regenerative Rankine cycle power plant for feedwater preheating purpose. The displaced extraction steam can then expand further in the steam turbine to generate power. In such a power plant, using the (concentrated) solar thermal energy to displace the extraction steam to high pressure/temperature feedwater heaters (i.e. displaced feedwater heaters) is the most popular arrangement. Namely the extraction steam to low pressure/temperature feedwater heaters (i.e. non-displaced feedwater heaters) is not displaced by the solar thermal energy. In a Solar Aided Power Generation plants, when solar radiation/input changes, the extraction steam to the displaced feedwater heaters requires to be adjusted according to the solar radiation. However, for the extraction steams to the non-displaced feedwater heaters, it can be either adjusted accordingly following so-called *constant temperature* strategy or unadjusted i.e. following so-called *constant mass flow rate* strategy, when solar radiation/input changes. The previous studies overlooked the operation of non-displaced feedwater heaters, which has also impact on the whole plant's performance. This paper aims to understand/reveal the impact of the two different operation strategies for non-displaced feedwater heaters on the plant's performance. In this paper, a 300 MW Rankine cycle power plant, in which the extraction steam to high pressure/temperature feedwater heaters is displaced by the solar thermal energy, is used as study case for this purpose. It was found that plant adopting the constant temperature strategy is generally better than that adopting the constant mass flow rate strategy. However, if rich solar energy is available, adopting the constant mass flow rate strategy can achieve better performance.

1. Introduction

In recent years, environmental issues around fossil fired power plants have led to solar thermal power plants attracting more attention. Different sunlight heating system has been evaluated [19]. However, solar thermal power plants have the disadvantage of higher costs when compared with lower cost fossil fired power plants. Therefore, a hybrid power system, integrating solar thermal energy into a conventional fossil fired power plant, has become an attractive option [12]. One hybrid power system uses solar thermal energy to preheat the feedwater of a regenerative Rankine cycle (an RRC) power plant [31]. Using this system, the extraction steam of the power plant, which is bled from the steam turbine to preheat the feedwater in a feedwater heater (FWH), can be displaced by the solar thermal energy. The displaced extraction steam is then expanded further in the steam turbine to generate power. This kind of power plant is known as a Solar Aided Power Generation (SAPG) plant [7,8]. The thermodynamic benefit of the SAPG plant comes from the displaced high quality (i.e. high temperature) extraction steam [26,27]. This technology has advantage of higher solar thermal to power efficiency than the solar alone power plant [30]. Also, the exergy losses of the RRC plant are decreased after the solar thermal input [4,5].

In an SAPG plant with multi-stages of extraction steam (i.e. with different temperature), the solar thermal energy is often used to displace part stages of extraction steam, not all the stages of extraction steam. It was found that solar thermal energy used to displace higher temperature extraction steam leads to greater solar thermal to power efficiency than that used to displace lower temperature extraction steam [28,29]. Zhao and Bai [32] also got the same results from an exergy perspective. In a typical RRC power plant, the FWHs include the high pressure/temperature FWHs, deaerator (DEA) and low pressure/temperature FWHs. Since the DEA is used for removing the oxygen from the feedwater, the extraction steam to the DEA is not displaced by the solar thermal

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Nomenclature

P_{solar}	annual power output from solar thermal energy, kW h
$\dot{Q}_{Boiler}$	variation of the re-heater load after the solar thermal input, kW
$\dot{Q}_{Solar}$	useful solar thermal power input into the power plant, kW
$\dot{Q}_{solar,on}$	solar thermal power falling on the solar collector, kW
W_{Ref}	power output from the reference RRC plant, kW
W_{Solar}	instantaneous solar power output, kW
W_{Total}	total electricity power output from the SAPG plant, kW
x_{Solar}	instantaneous solar share, %
$\eta_{Net\ solar}$	annual net solar-to-power efficiency, %
η_{Solar}	instantaneous solar thermal to power efficiency, %

Abbreviation

CT	constant temperature strategy
CM	constant mass flow rate strategy
DEA	deaerator
DNI	Direct Normal Insulation
FWH	feedwater heater
HTF	heat transfer fluid
LCOE	Levelized Cost of Electricity
RRC	regenerative Rankine cycle
SAPG	Solar Aided Power Generation
SP	solar preheater

energy. Some previous studied made a comparison between the displacement of the extraction steam to high pressure/temperature FWHs and low pressure/temperature FWHs. It was found that the displacement of extraction steam to low pressure/temperature FWHs has no significant effect on the performance of the SAPG plant [22]. Also, considering the overloading of the last turbine stages, the displacement of extraction steam to all high pressure/temperature FWHs is the best option for an SAPG plant [14]. Therefore, most subsequent studies about SAPG plants assumed that solar thermal energy is only used to displace the extraction steam to high pressure/temperature FWHs (i.e. displaced FWHs). This means that the extraction steam to low pressure/temperature FWHs (i.e. non-displaced FWHs) is not displaced by the solar thermal energy.

In an SAPG plant, when the solar radiation/input changes, the extraction steam should be adjusted responding to the variations of solar thermal input. Under the condition of only extraction steam to high pressure/temperature FWHs is displaced by the solar thermal energy, these extraction steam should be decreased (i.e. displaced) according to the solar thermal input. However, for the extraction steam to low pressure/temperature FWHs (i.e. non-displaced FWHs), which is not displaced by the solar thermal energy, these extraction steam can also be adjusted according to the solar thermal input. This is termed as non-displaced FWH operation strategy.

The impact of the non-displaced FWH operation strategies on the SAPG plant's performance has been overlooked by previous studies. Most of previous studies did not clearly defined the non-displaced FWH operation strategies that they are adopted. Based on the assumption that only extraction steam to high pressure/temperature FWHs has been displaced, Bakos and Tsechelidou [2] assessed the energy production cost and payback time of an SAPG plant, Pierce et al. [15] compared the cost of the SAPG plant with the solar alone power plant, Peng et al. [16–18] evaluated the SAPG plant under off-design condition of the power plant, and Zhu et al. [35,36] evaluated the solar contribution of the SAPG plant from exergy perspective. Zhao et al. [33,34] used a different criteria to optimise the SAPG plant modified from different capacity. Zhou et al. [37] used evaluated the SAPG plant with different solar collectors. Zhai et al. [38,39] optimised the solar contribution by adjusting the solar thermal fluid. Recently, Feng et al. [3] evaluated the thermodynamic-economic performance of the SAPG plant. However, these studies without mentioning the operation of the non-displaced feedwater heaters. Some other studies are based on a non-displaced FWH operation strategy that remains the feedwater outlet temperature of the non-displaced FWHs unchanged. Based on this strategy, Hou et al. [9,10,11] evaluated an SAPG plant, which is modified from a 300 MW power plant, with different collector areas to achieve the lowest Levelized Cost of Electricity (LCOE). Also, Wu et al. [23,24,25] evaluated an SAPG plant with a storage system. However, there are still some other previous studies based on the non-displaced FWH operation strategy that remains the extraction steam flow rates to non-displaced FWH unchanged [28,29]. Qin and Hu [20] evaluated the SAPG plant based on this strategy. It is obvious that most of previous studies have not clearly define their non-displaced FWH operation strategy. For an SAPG plant, the technical benefit comes from the extraction steam [26,27]. Although the extraction steam to non-displaced FWHs is not displaced by the solar thermal energy, their operation strategies still can impact the SAPG plant's performance. SAPG plant adopting different non-displaced FWH operation strategies would lead different technical performance. However, the impact of the non-displaced FWH operation strategy is lack of study. The comparison of different non-displaced FWH operation strategies is a gap in the extant studies.

The present paper aims to understand/reveal the impact of the non-displaced FWH operation strategies on the SAPG plant's performance in terms of the instantaneous and annual solar power output, solar share and solar efficiency.

2. Operation of non-displaced FWH in an SAPG plant

In an SAPG plant, the solar thermal energy carried by the heat transfer fluid (HTF) is used to displace some extraction steam through a heat exchanger (a solar preheater, or SP) to preheat feedwater. The SP facilitates heat transfer process between the HTF and feedwater of power plant.

2.1. Displaced FWH and non-displaced FWH

In an SAPG plant, the feedwater heaters of which the extraction steam is displaced (by solar heat) are termed as *Displaced feedwater heaters*. Other feedwater heaters of which the extraction steam is not displaced are termed as *Non-displaced feedwater heaters*. Fig. 1 presents a simplified SAPG plant, in which the solar thermal energy is used to displace the extraction steam to high pressure/temperature FWHs while the extraction steam to the DEA and low pressure/temperature FWHs is not displaced (by the solar thermal energy).

2.2. Non-displaced FWH operation strategies

In an SAPG plant as shown in Fig. 1, the mass flow rates of the extraction steam to displaced FWHs (i.e. extraction steam at points