Energy Conversion and Management 124 (2016) 155–167

Contents lists available at ScienceDirect

Energy Conversion and Management

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

The performance of a Solar Aided Power Generation plant with diverse "configuration-operation" combinations

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ARTICLE INFO

Article history:
Received 3 May 2016
Received in revised form 16 June 2016
Accepted 5 July 2016
Available online 14 July 2016

Keywords:
Solar Aided Power Generation
Solar preheater configuration
Solar preheater operation strategy
"Configuration-operation" combinations
Power boosting

ABSTRACT

Solar Aided Power Generation is an efficient way to integrate solar thermal energy into a fossil fuel fired power plant for solar power generation purposes. In this particular power plant, the solar heat is used to displace the extraction steam to preheat the feedwater to the boiler. The heat exchanger, which facilitates the heat exchange between the solar heat carried by the heat transfer fluid and the feedwater, is termed a solar preheater. Four possible configurations of the solar preheater, namely Parallel 1, Parallel 2, Series 1 and Series 2, are proposed in this paper. In this type of plant, the extraction steam flow rates must be adjusted according to the solar input. The ways to control the extraction steam flow rates are termed solar preheater operation strategies. Three typical strategies: the Constant Temperature control, Variable Temperature control with high to low temperature feedwater heater displacement and Variable Temperature control with low to high temperature feedwater heater displacement have been identified. Each configuration can be operated with one of the three strategies, resulting in twelve "configuration-operation" combinations/scenarios (shown in Table 1). Previous assessments and modelling of such a plant have only been based on a single combination. In this paper, a Solar Aided Power Generation plant, modified from a typical 300 MW power plant, is used to understand the plant's performance for all twelve of the available combinations. The results show that the instantaneous and annual technical performances of such a plant are dependent on the combinations used. The scenario 10 (Table 1) is superior to the other combinations in terms of the plant's instantaneous technical performance, while the scenarios 2, 5, 8 (Table 1) has the best plant's annual technical performance.

1. Introduction

In recent years, integrating solar thermal energy into a fossil fired power plant has been attracting more attention [14]. It was found that this type of hybrid power plant has both technical advantages [16] and economic advantages [24,30], over a solar alone power plant. Solar Aided Power Generation (SAPG) is a technology in which solar thermal energy, carried by a heat transfer fluid (HTF), is used to displace the extraction steam of a Regenerative Rankine Cycle (RRC) power plant, by preheating the feedwater of a power plant. The displaced extraction steam can then be further expanded in the steam turbine to generate additional power. In such a power plant, the solar thermal to power efficiency of low-to-medium solar heat can be improved [10] and the exergy losses of the power plant can be reduced [8,9]. Recently, Feng et al. [6] found that the thermos-economic benefit of an SAPG plant is higher than that of a stand-alone solar power plant.

In an SAPG plant, the heat exchange between the HTF and feedwater occurs in solar preheaters (SP), i.e. heat exchangers. Hu et al. [10] evaluated an SAPG plant where the SP is in parallel with the feedwater heaters (FWHs). Furthermore, Hou et al. [11] assessed the SAPG's annual performance where an SP is in series with the FWHs. Depending on the SP's locations relative to the FWHs, the SPs could have either a parallel or a series configuration. Based on these different configurations, the mass flow rates of the extraction steam should be adjusted according to the solar input. The method of adjusting the extraction steam is termed an SP operation strategy. The specific configuration and their possible operation strategy are termed "configuration-operation" combinations. As the displacement of extraction steam at the higher temperature stage leads to higher thermodynamic benefit [27,28],, an SAPG plant with different combinations would have different thermodynamic performances.

The previous studies of SAPG plants were all based on a single configuration-operation combination. Thus, the SP configurations and their possible operation strategies have not been clearly defined, let alone studied. Most previous investigations of SAPG

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http://dx.doi.org/10.1016/j.enconman.2016.07.015
0196-8904/

Nomenclature

C_F	specific heat capacity of the HTF, kJ/kg °C
h_i, h_i'	specific enthalpy of the steam at the inlet and outlet of the turbine stage, kJ/s
$\dot{m}_{Dr}$	flow rate of the drained steam, kg/s
$\dot{m}_{Ex}$	flow rate of the extraction steam, kg/s
$\dot{m}_{FW\ In}$	flow rate of the feedwater entering into the FWH, kg/s
$\dot{m}_{HTF}$	HTF flow rate sent to SPs from the solar field, kg/s
$\dot{m}_i$	flow rate of each stage through i (i = 1–8) stage of the steam turbine, kg/s
$\dot{m}_j$	flow rate of extraction steam at each extraction point (j = A to H), kg/s
$\dot{m}_0$	flow rate of steam inlet steam turbine, kg/s
q_i	specific enthalpy decrease of extraction steam in the *i*th FWH, kJ/kg
$\dot{Q}_{Solar}$	solar thermal energy carried by the HTF to replace the extraction steam, kJ/s
$\dot{Q}_{Solar,i}$	average solar thermal power input into the *i*th FWH to replace the extraction steam for each FWH, kJ/s
$\dot{Q}_{Solar,i,max}$	maximum solar energy needed for *i*th FWH, kJ/s
r_i	specific enthalpy decrease of the drained steam from the $(i-1)$th FWH in the *i*th FWH, kJ/kg
W	power output from the steam turbine, kW
W_{Solar}	power output from the SAPG plant, less that from the reference plant, kW
y_j	$\dot{m}_j/\dot{m}_0 (j = A\ to\ H)$
$\eta_{Net\ solar}$	annual net solar thermal to power efficiency, %
η_{Solar}	instantaneous solar thermal to power efficiency
τ_i	specific enthalpy increase of FW in the *i*th FWH, kJ/kg

Abbreviations

CT	constant temperature strategy
DEA	deaerator
DNI	Direct Normal Insulation
FWH	feedwater heater
HTF	heat transfer fluid
P1	Parallel 1
P2	Parallel 2
RRC	Regenerative Rankine Cycle
SAPG	Solar Aided Power Generation
SP	solar preheater
SPAME	Specific Parameters and Matrix Equation
S1	Series 1
S2	Series 2
VT-HL	high to low varying temperature strategy
VT-LH	low to high varying temperature strategy

Subscripts

i	*i*th stage FWH
j	stage of extraction point

plants have been undertaken with parallel configurations. Based on this configuration, Yang et al. [29] found that the displacement of extraction steam with the highest temperature (i.e. where the SP is in parallel with the highest temperature FWH) leads to the highest solar to power efficiency. Later, Zhao and Bai [31] found the same result by using the annual hourly solar radiation data. Therefore, some later studies were based on the configuration whereby the SP is only in parallel with the highest temperature FWH. The extraction steam to highest temperature FWH is adjusted to retain the feedwater outlet temperature, unchanged. Bakos and Tsechelidou [3] found that an SAPG plant based on this configuration would have the advantage of lower energy production costs. Also, Pierce et al. [19] indicated that the cost of the SAPG plant is about 72% of a stand-alone concentrating solar power plant. Based on the same configuration, Peng et al. [20] evaluated an SAPG plant with different solar collectors' axis tracking modes. Later, Peng et al. [21,22], used the hourly solar radiation data to simulate the same SAPG plant. It was found that the exergy destruction of the SAPG plant is lower than that for a stand-alone solar power plant. Recently, based on the same configuration, Zhu et al. [37] analysed an SAPG plant modified from a 1000 MW, 600 MW and 330 MW plant and Burin et al. [2] evaluated an SAPG plant modified from a sugarcane plant. Recently, Zhai et al. [36] evaluated the thermos-economic cost of an SAPG plant based on this configuration. In another study, Popov [18] indicated that having an SP in parallel with all high temperature FWHs is the best option for an SAPG plant. Therefore, some studies are based on the configuration whereby the SP is in parallel with all high temperature FWHs. Based on this configuration, Zhao et al. [32,33], analysed an SAPG plant with different loads of plant. Later, Hou et al. [12] evaluated an SAPG plant for fuel saving purposes by using the annual hourly solar radiation data and Zhai et al. [34] compared SAPG plants with and without any storage system. These studies are based on the operation strategy that the extraction steam to high temperature FWHs is adjusted to maintain the feedwater outlet temperature of each high temperature FWH unchanged, i.e. a constant temperature operation strategy. In this combination, the extraction steam to all high temperature FWHs is reduced simultaneously, according to solar input.

Some recent papers about SAPG plants are based on the series configuration. Hou et al. [11] and Wu et al. [25] evaluated a 300 MW SAPG plant using hourly solar radiation data in Lhasa. Zhai et al. [35] evaluated a 660 MW SAPG plant. In their studies, the SP is located between the deaerator and high temperature FWHs and used to displace extraction steam to all high temperature FWHs. Recently, Wu et al. [26] evaluated a series configuration's SAPG plant with different storage capacities. The operation strategy of their studies is based on the constant temperature strategy. In this combination, the extraction steam is displaced in order from lower to higher temperature extraction steam. In an SAPG plant, the mass flow rates of extraction steam can also be adjusted at varying the feedwater outlet temperature, i.e. the varying temperature operation strategy. By using this strategy, the higher temperature extraction steam can be prior displaced by the solar thermal energy, which leads to greater thermodynamic benefits. Each configuration can be operated with one operation strategy. This means that an SAPG plant has alternative "configuration-operation" combinations. However, the possible "configuration-operation" combinations of a SAPG plant have not been clearly proposed. Comparison of different combinations is a gap in the extant studies.

In the present paper, the first aim is to present the possible "configuration-operation" combinations of an SAPG plant. The second aim is to compare the technical performance of an SAPG plant with all possible "configuration-operation" combinations. In particular, the instantaneous technical performance of an SAPG plant with the same solar input and the annual technical performance of an SAPG plant with the same solar field area are evaluated.