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Thermal performance of different integration schemes for a solar tower aided coal-fired power system

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ABSTRACT

A Solar Tower Aided Coal-fired Power (STACP) system utilizes a solar tower coupled to a conventional coal-fired power system to reduce pollutants, greenhouse gas emissions and the investment of solar energy facilities. This paper examines three different schemes for integrating solar energy into a conventional boiler. For each scheme, an energy and exergy analysis of a 600 MW_e supercritical coal-fired power system is combined with 53 MW_{th} of solar energy in both a fuel saving mode and a power boosting mode. The results show that, for all these integration schemes, the boiler's efficiency and system's efficiency are reduced. However, the standard coal consumption rate is lower in comparison to conventional power plants and the standard coal consumption rate in the fuel saving mode is lower than that in the power boosting mode for all three schemes. Comprehensively considering both the standard coal consumption rate and efficiency, the scheme that uses solar energy to heat superheat steam and subcooled feed-water is the best integration option. Compared with a coal-fired only system, the saved standard coal consumption rate of the above mentioned scheme in fuel saving mode and power boosting mode can reach up to 11.15 g/kWh and 11.11 g/kWh, respectively. Exergy analysis shows, for STACP system, exergy losses of boiler and solar field contribute over 88% of whole system's exergy loss.

1. Introduction

Air pollution and global warming have been posing a serious threat to human health and the environment, which is mainly caused by the use of fossil fuel. In China, over 70% of the electrical demand is met by coal-fired power generation stations [1,2], which contributes a large proportion of greenhouse gas and pollution emissions. In this matter, the Chinese government has taken effective emergency measures in order to address these problems. One way to deal with this situation is to exploit renewable energy to replace coal-fired power generation. Of all the renewable energy, concentrated solar power, which can be built in large scale, is a promising technology that can meet the power demand for China. However, at present, the solar-only thermal power plant still cannot be built at such a large scale because the cost is extremely high and the annual global efficiency is low. Because the steam cycle of solar thermal power plant is similar to that of a coal-fired power plant, integrating solar thermal energy into coal-fired power plant, also known as solar aided coal-fired power (SACP) system, is not only to reduce greenhouse gas emissions but also to reduce the investment in solar energy facilities.

A SACP system was first studied by Zoschak and Wu in 1975 [3]. Seven possible methods of integrating solar energy to a coal-fired power system were proposed and analyzed. Results show that combing solar energy with the evaporation and superheating is the most preferred method due to the high utilization of solar energy, and using solar energy to preheat feed-water is also a favorable method. However, in the most recent studies related to SACP systems, solar energy is used to preheat feed-water [4–8], and the focus is mainly on evaluating different integration schemes, operation modes and its thermal and economic performances. For the system integration aspect, Hu et al. used solar energy to replace the extracted steam to heat the feed-water. Results showed that the higher the temperature aided heat source is, the more beneficial the system can be [9]. Yang et al. considered a 200 MW_e coal-fired unit as an example and explored four different integration schemes in fuel saving mode and power boosting mode [10]. In terms of operation modes, Qin et al. proposed four possible SACP system configurations and three operation strategies. Therefore, an SACP system with twelve potential "configuration-operation" combinations was investigated [11]. They studied the impact of the two different operation strategies for non-displaced feed-water heaters on the plant's performance. The results indicated that a plant with a constant temperature strategy is generally better than one operating with a

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constant mass flow rate strategy [12]. Recently, they proposed a mixed operation mode, in which the SACP system can be operated at a series of time intervals and, in each time interval, the system operated in either power boosting or fuel saving mode. The results showed that the annual profitability of such a mixed operation mode could be up to 12.1% higher than that of a single operation mode [13]. In the area of thermal performance of a SACP system, Hou et al. investigated the performance of a SACP system at the design point under various load conditions and the performance in fuel saving mode under different solar radiation conditions [14,15]. Huang et al. discussed the influences of power station capacities and sizes of solar field on the performance of the SACP system [16]. Adibhatla et al. conducted exergy and thermo-economic analyses on a 500 MW_e SACP plant. The exergy analysis showed that the solar field and boiler have the two highest exergy destruction ratios (78.90% and 56.52%) and the thermo-economic analysis showed that the product cost rate of the generator was 19.1 USD/kJ [17]. Li et al. studied the performance of the SACP system based on the all-condition mechanism model of the SACP system [1]. Hong et al. demonstrated the performance behaviors of a 330 MW_e SACP plant under off-design conditions by applying the derived expressions of the conversion of solar energy into power [18]. From the economic aspect, Wu et al. explored the annual economic performance of the SACP system under different tracking modes, aperture areas, and storage capacities [19]. Adibhatla et al. used an energy, exergy, economic and environmental (4E) method to analyze the SACP system [20]. Wang et al. optimized the solar multiple for a SACP system from the technical and economic aspects, the results showed that the efficiencies in the region of 13–20% can be achieved and the reduction in the levelized cost of electricity was in the region of 0.7–1.1 ¥/kWh [21]. Various ways of evaluating SACP systems have been used. Zhai et al. evaluated the SACP system using a life cycle assessment method [22]. Peng et al. evaluated the system using an energy-utilization diagram methodology [23]. Zhai et al. proposed an evaluation method named solar contribution evaluation method, based on the second law of thermodynamics and exergy balance, and distinguished the difference of exergy efficiency between solar and coal in the SACP system [24]. Hou et al. proposed a new evaluation method of solar contribution in a SACP system based on exergy analysis [25].

In combining solar energy with the evaporation and superheating areas, due to the high temperature of steam/water in the boiler, solar tower technology is an ideal option to consider. Zhang et al. proposed two schemes of the solar tower aided coal-fired power (STACP) system, where the standard coal consumption rate could be reduced by more than 17 g/kWh and a flue gas bypass was introduced to avoid high thermal stress across its support frame [26]. In their following work, the annual performance of the two schemes with thermal energy storage, using a single-tank thermocline technology, were investigated. Results showed that the solar power efficiency was around 16–20% [27]. Zhu et al. applied exergy and advanced exergetic analysis methods to a STACP system and found maximum exergy loss occurs in the boiler (53.5%), followed by the solar field (26%) [28]. Then, they studied the annual performance of a STACP system and found that the annual average coal consumption rate of STACP system is 27.3 g/kWh lower than that of coal-fired power system and the annual average CO_2 emission rate of STACP system is reduced by 10.1% compared with that of coal-fired power system [29].

There has been much research regarding solar energy integration to preheat feed-water, and limited efforts have been made on integrating solar energy with evaporation and super-heating. Because of the temperatures involved and the need to improve the cycle efficiency, the temperatures available from a solar tower system are more suitable to utilize with evaporators and super-heaters in a conventional boiler system. In this paper, three different schemes for integrating solar energy into a boiler are proposed under either a fuel saving mode or a power boosting mode with same solar energy input. In scheme 1, solar energy is used to heat part of the superheat steam. In scheme 2, solar energy is used to heat part of the feed-water and superheat steam. In scheme 3, solar energy is used to heat part of the feed-water, superheat and reheat steam. Both fuel saving and power boosting modes share the same system configuration, and the only difference between these two operation modes is the coal consumption input. In the fuel saving mode the overall power output is kept constant, and coal input to the power system is reduced when solar energy is available. In the power boosting mode, additional power is produced, and coal input to the power system is constant when solar energy is available. A total of 6 cases are studied in this paper and the following abbreviations are used to refer to each: scheme 1 in fuel saving mode (FS1), scheme 1 in power boosting mode (PB1), scheme 2 in fuel saving mode (FS2), scheme 2 in power boosting mode (PB2), scheme 3 in fuel saving mode (FS3), and scheme 3 in power boosting mode (PB3). This study has three main novel features in comparison to our own studies [28]: (1) The boiler model is established in detail instead of treating it as a “black box”. (2) The performances of the three different integration schemes under both fuel saving mode and power boosting mode are investigated and compared from both energy and exergy aspects. (3) Sankey diagrams are incorporated to analyze and compare the exergy performance between coal-fired power system, FS2 and PB2.

2. System description

2.1. Solar tower aided coal-fired power system

Fig. 1 shows a schematic of the STACP system, which contains the solar field and the coal-fired power plant. The solar field is composed of many heliostats, a solar tower, a columnar receiver, and a heat exchanger. In the solar field, solar energy is reflected onto a receiver that is at the top of the tower by the heliostats. Molten salt passes through the receiver to absorb the solar energy and the thermal energy of the molten salt is then transferred to the steam/water cycle in separate heat exchangers. The molten salt used in this study is a mixture of 60 wt% $NaNO_3$ and 40 wt% KNO_3. The thermal properties of the molten salt are a function of temperature as follows [30]:

$$\rho = 2263.72 - 0.636T \tag{1}$$

$$c_p = 1396.02 + 0.172T \tag{2}$$

$$\lambda = 0.391 + 0.00019T \tag{3}$$

where, ρ is the density of molten salt, kg/m^3; c_p is the specific heat of molten salt at constant pressure, J/(kg K); λ is the thermal conductivity of molten salt, W/(m K); T is the temperature of molten salt, K.

A conventional 600 MW_e supercritical coal-fired power plant is considered in this paper and the thermal parameters of the main steam and reheat steam are 566/24.2 and 566/3.6 (°C/MPa), respectively. In the coal-fired power plant, the unsaturated feed-water from the condenser enters the boiler after going through the condensate pump, four low pressure heaters (H5, H6, H7, and H8), a deaerator, feed-water pump and three high pressure heaters (H1, H2, and H3). Then the feed-water absorbs heat in the boiler and becomes superheat steam. The outlet superheat steam from the boiler is transported to the high pressure turbine (HP) to produce power. The steam from the HP goes into the boiler to be reheated in order to improve its work capacity. Then the reheat steam is transported to the intermediate pressure turbine (IP) and low pressure turbine (LP) to produce power. Finally exhaust steam is condensed in the condenser.

2.2. Physical models of different integrating schemes

Fig. 2 shows main components for the three integrating schemes. Feed-water from the high pressure heaters first goes to the economizer (ECO), and then to the water wall from the bottom of the boiler. In this the feed-water partially turns into steam due to radiative heat absorption from the flame in the furnace. Then steam/water mixture enters to