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Thermodynamic performance study on solar-assisted absorption heat pump cogeneration system in the coal-fired power plant

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ABSTRACT

A new cogeneration system which integrates a solar-assisted absorption heat pump (SAAHP) into a coal-fired power plant for waste heat recovery of exhausted steam from a steam turbine is presented to improve utilization efficiency of fossil fuels. This study compares the performances of three cogeneration systems which differ in their driving heat source of AHP in the heating system. The following cogeneration systems are considered: conventional cogeneration system (CCS), cogeneration system with AHP driven by extracted steam (CSAES) and cogeneration system with AHP driven by solar (CSAS). Compared with the CCS and CSAES, output power respectively increases by about 11.43 and 6.48 MW; coal consumption rate reduces by 26.27 and 14.29 g/kWh in the CSAS with 11529 kJ heating capacity at 100% THA (Turbine heat acceptance) condition. The integral thermal and exergy efficiency of the CSAS are 58.32% and 36.26%. Meanwhile, reduced coal consumption rate and increased power both increase with increasing heating capacity. It is found that thermal efficiency and exergy efficiency for solar energy utilization both increase with the increasing load.

1. Introduction

With increasingly highlighted problems of energy resource shortage and pollutant emissions due to increasing consumption of fossil energy, the renewable energy sources have been considered to be an appropriate alternative [1]. Many countries have promulgated encouraging policies to promote renewable energy developing, and the renewable energy has been paid more and more attention in the research, such as wind, biomass energy and solar etc. [2]. Especially the solar energy accounting for 99% of the renewable energy with huge reserves, wide distribution and clean utilization has become a favorite energy resource [3]. However, some puzzles hinder practical production in a pure renewable energy application form currently, including technological problems and higher costs, etc [4]. At present, the thought of coupling the renewable energy with fossil energy seems to be an effective way to utilize the clean energy [5,6]. The coal is main energy resource and coal-fired power plant is main electric generation form in China, which has a huge energy alternative potential. Considering the economy and stable operation, modifying these existing coal-fired power plants is more beneficial instead of reconstructing lots of new power plants [7]. Therefore, it is a practical way to couple solar heat with existing coal-fired power plants. The integrated mode can not only make full use of wide adjusting range of the original units in the power plant but also eliminate operating instability and reduce generated power cost in the solar-only power plant [8].

For the sake of exploring new schemes for solar thermal energy utilization in the existing coal-fired power plants, many studies in the field have been accomplished in recent years. You and Hu [9] firstly proposed a novel integrated system in which the extracted steam was replaced by solar heat for heating feed water in a three-stage regenerative Rankine plant. Zhao et al. [10] analyzed the thermodynamic performance of all alternative schemes for each extracted steam in the regenerative system. The results indicated that the system effect is the best when the second extracted steam was replaced. Peng et al. [11] simultaneously discussed the performance of solar-only power plants without storage and solar-hybrid coal-fired power plants, and revealed the superiority of the hybrid systems. In the following study, they continued to analyze the thermodynamic performance under off-design operations [12]. Wu et al. [13] simulated and analyzed the hourly based annual performance on a 330 MW solar-aided coal-fired power plant equipped with various thermal energy storage (TES)

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capacities and solar field sizes at different loads. Zhai et al. [14] applied the thermo-economic structural theory to analyze the performance of solar-aided coal-fired power system in two operating modes, namely, fuel-saving and power-boosting mode. In the following work, they continued to evaluate pollutant emission and primary energy consumption of the solar-aided coal-fired power system with and without thermal storage by life cycle assessment [15].

Theses researches supply a certain theoretical support for solar energy utilization in the coal-fired power plants. However, they generally consider the coal-fired pure power generation systems, rather than electricity-heating cogeneration as presented in the paper. Additionally, the waste heat at the cold end of the power plant is ignored. Cogeneration that simultaneously generates electricity and heat has been recognized as an efficient energy utilization mode and rapidly developed around the world [16]. Meanwhile, the waste heat of exhausted steam from the steam turbines which is generally discharged into the environment through a condenser accounts for more than fifty percent of the total energy inputted into power plants [17]. In this case, it not only leads to a lot of energy loss, but also low efficiency of energy utilization as well as pollution to the environment. The advantage of AHP utilization for waste heat recovery has been confirmed by a number of studies [18,19].

The aim of the paper is to explore a novel way to achieve the double benefits of renewable energy resource utilization and waste heat recovery for the fossil fuel, and make various available energy resources to be fully used. According to the first and second law of thermodynamics, a 135 MW direct air-cooling unit in a coal-fired power plant is considered as a case analysis to exhibit the performances of the three cogeneration systems, namely, conventional cogeneration system (CCS), cogeneration system with AHP driven by extracted steam (CSAES) and cogeneration system with AHP driven by solar (CSAS). A comparative study is carried out to discuss the performance and exergy evaluating indicators among the three heating modes under various operating loads and heating capacities. Meanwhile, output power increment, heating capacity increment, coal consumption rate decrement, and the change of total energy and exergy efficiency are also quantitatively revealed after the modification.

2. System description

The diagrams of the three cogeneration systems are respectively shown in Fig. 1a, (b), (c). The main steam parameter and pattern of the power plant is CZK 135–13.24/0.245/535/535.

2.1. Conventional cogeneration system (CCS)

As illustrated in Fig. 1a, the return water (Node 37) from HC (heat consumer) is only heated by the HE (heat exchanger) of HN (heating network) whose heat source (Node 30) comes from the fifth stage extracted steam in the CCS. The hydrophobic (Node 31) flows into 4# LPH to be heated and ultimately returns into the boiler.

2.2. Cogeneration system with AHP driven by extracted steam (CSAES)

As shown in Fig. 1b, the return water (Node 37) is designed to be heated by AHP whose driving heat source (Node 32) comes from the fifth stage extracted steam, then heated by HE in the CSAES, instead of being only heated by HE in the CCS. The low-temperature heat source (Node 34) is derived from exhausted steam from the steam turbine (ST). The two branches of hydrophobic (Node 33 and 35) both flow into air-cooling system (ACS) to be further condensed and return into the boiler afterwards. Some high-parameter extraction steam that should have been extracted to heat return water can be saved and returns into the ST to do extra work.

2.3. Cogeneration system with AHP driven by solar (CSAS)

As illustrated in Fig. 1c, the original driving heat source (Node 32) of AHP system is completely or partially replaced by the heat source from SCS (solar collectors) (Node 40) when the sunshine is adequate or not enough. The hydrophobic (Node 41) returns into the collectors to achieve the recycle and its parameters are kept the same as that of Node 33. It can save more high-parameter steam and generate more extra power. It can not only save fossil energy source consumption and reduce pollutant emissions, but also achieve the double effects of waste heat recovery and renewable energy utilization. The CSAS will restore to the CSAES when the SCS does not work due to some reasons, such as rainy, night and so on.

The schematic diagram of the heating system with AHP driven by solar collectors and heat exchanger (AHP-SC-HE) is shown in Fig. 2 in which the parameter numbers in parentheses are corresponding to those in Fig. 1c. The working medium firstly absorbs heat released by a part of exhausted steam from the ST in the evaporator and then releases the heat to return water in the absorber. The heat released from the SCS is absorbed by the working pairs in the generator and then release to heat return water in the condenser. The return water is heated from 55 °C to 75 °C by AHP system, and then continues to be heated to 85 °C by the HE and eventually supplied for heat consumer. The heat increasing type AHP is selected whose working pairs are Lithium Bromide and water [20]. The parabolic trough solar collectors are selected in the CSAS [21].

3. Modeling

The thermal parameters of the key design points are listed in Table 1. In building thermodynamic models, some assumptions are given as following:

(1) There is no change in the state parameters of each node in original CCS before and after the modification.
(2) Any performance variation is ascribed to variation of mass flow rate.
(3) The power consumption of the pumps is neglected.
(4) There are no water or steam leakage and heat loss in facilities and pipelines.
(5) The hydrophobic parameters evolved from driving and low-temperature heat source in CSAS are the same as that of CSAES.
(6) The whole system is in a stable operating condition.

3.1. Heating system

The operating process of key components of the heating system can be expressed as following:

Generator (Node: 49 → 43, 50) and (32 (or 40) → 33 (or 41)):

The lithium bromide-water absorbs heat energy from driving heat source in generator. The balance equations can be expressed as follows:

$$D_{dhs}(h_{32} - h_{33}) = D_r h_{43} + D_{ss} h_{50} - D_{ws} h_{49} \quad (1\text{-}1)$$