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Safety and efficiency assessment of a solar-aided coal-fired power plant

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ABSTRACT

Hybridizing solar energy with a coal-fired power plant has proven to be an efficient way of reducing coal consumption and discharged pollutants. In this study, solar energy was employed to heat boiler inlet feedwater through a solar high-pressure feedwater heater H0 to increase its temperature. Solar-aided feedwater heating of a N600-24.2/566/566 supercritical coal-fired power plant is discussed as a case study. An all-condition mechanism model (ACMM) of SACFPP was proposed and simulated by MATLAB/Simulink. The maximum solar energy input for the safe operation of a boiler was determined as 66,544 kW based on ACMM simulation results. Moreover, the boiler efficiency and solar-to-electricity efficiency plummeted as solar energy input increased. The solar-to-electricity efficiency decreased from 23.33% to 20.33% when the solar energy input increased from 16,636 kW to 66,544 kW (in 100%THA). The solar-to-electricity efficiency decreased from 16.76% to 13.29% when the solar energy input increased from 16,636 kW to 66,544 kW (in 35%BMCR). A high unit load corresponds to high solar-to-electricity efficiency. SACFPP had a high coal saving rate when it operated in a lower load condition.

1. Introduction

Nowadays, coal-fired power plants supply most of the electricity worldwide. Serious environmental problems are caused by coal combustion in coal-fired power plants (CFPP). Solar energy, as a clean and abundant energy that limits emitted pollution, has increasingly attracted attention [1]. However, traditional standalone solar plants (SASP) occupy a large area and have poor efficiency and costly shortcomings, all of which hinder their large-scale utilization [2]. Integrating solar thermal energy into CFPP in a solar-aided coal-fired power plant (SACFPP) has the potential to reduce the use of coal in CFPP and overcome the drawbacks of SASP [3]. SACFPP has higher solar-to-electricity efficiency (SEE) and lower levelized cost of energy (LCOE) compared with SASP [4,5]. Research on SACFPP has mainly focused on system integration, system operation characteristics, economic analysis, and thermodynamic evaluation.

Several investigations have been conducted on the integration modes and influence of solar energy introduction [6,7]. Hybrid solar/coal power plant use solar energy in various ways, such as feedwater heating, steam superheating, steam reheating, and air preheating [8]. Many researchers are interested in solar-aided feedwater heating in SACFPP, which uses solar thermal energy carried by heat transfer fluid to displace extracted steam from turbines in CFPP [9,10]. Energy and exergy efficiencies of solar energy in SACFPP were higher than those in SASP [7]. The substitution of high-pressure (HP) turbine-bled steam has better performance compared with replacement of low-pressure turbine-bled steam [11,12]. Yan et al. compared the performance of solar energy with multi-point and multi-level integration for feedwater heating and found that solar-to-electricity efficiency with a solar input of 330 °C could be high as 45% and decreased to nearly 10% with a solar input of 85 °C [11]. Popov obtained the highest solar-to-electricity efficiency by using solar thermal energy to replace HP heaters together with economizer [12]. Non-displaced feedwater heater operations affected the performance of an entire plant [13]. Qin et al. compared 12 solar preheater (SP) combinations from four configurations and three operation strategies [14]. They found that SACFPP has the highest technical performance with the use of the S2 configuration (in which SP was located between the highest-temperature FWH and the boiler) and the CT strategy, in which the extraction steam flow rates to all high-temperature FWHs are adjusted to ensure that the feedwater outlet temperatures remain unchanged).

Some researchers have paid attention to economic analysis and thermodynamic/exergy evaluation of SACFPP and observed that the energy production cost of solar energy in SACFPP is lower than that of SASP [4,15]. Zhu et al. used 5 methods to evaluate the solar heat contribution in SACFPP based on exergy analysis [16]. They found that taking the second law of thermodynamics into consideration based on thermal economics is a practical method to evaluate solar contribution

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Nomenclature

B	coal consumption (kg)
F	radiant interchange coefficient
K	convective heat transfer coefficient kW/(m^2 °C)
P	power output (kW)
Q	heat capacity (kJ)
S	area (m^2)
T	temperature (°C)
b	standard coal consumption rate (g/kW h)

Greek symbols

η	efficiency
σ_0	Stefan–Boltzmann constant

Acronyms

ACMM	all-condition mechanism model
CFPP	coal-fired power plants
HP	high pressure
IP	intermediate pressure
LP	low pressure
SACFPP	solar-aided coal-fired power plant
SASP	standalone solar plants
SP	solar preheater
FWH	feedwater heater

Subscripts

bl	boiler
c	coal
con	convection
el	electricity
fw	feedwater
g	gas
he	heat
in	inlet
ma	main steam
out	outlet
ra	radiation
re	reheated steam
s	steam
sf	solar field
sol	solar

to electricity. Peng et al. evaluated the exergy of a 330 MW SACFPP and found that LCOE was 20–30% lower than that of SASP [17]. Zhao et al. found that relatively higher solar-to-electricity efficiency of SACFPP results from solar heat set at around 300 °C and through the high energy level of the replaced steam extractions, high collector efficiency, and high turbine internal efficiency [18]. Zhai et al. evaluated the thermo-economic cost of SACFPP modified from a 1000 MW CFPP and found indicators for its energy-saving capacity and emission reduction [8]. The thermo-economic cost of electricity increased by 16.9–21.6% due to the large investment in solar components. Feng et al. developed a general thermal economic analysis method for SACFPP on the basis of the thermodynamic cycle [19]. Another investigation that used off-design performance analysis was also conducted under fluctuant direct normal insolation [20–22].

The abovementioned research presented different perspectives on integrating solar thermal energy with feedwater heating to reduce extracted steam from turbines. Proper integration of solar heat with feedwater could achieve higher power efficiency than traditional SASP technology could. The coal consumption rate for power generation decreased by 17 g kW^{-1} h^{-1} for SACFPP compared with 660 MW supercritical coal-fired power plants [23]. Solar power efficiency was around 16–20% [24]. In fuel-saving operation mode, the temperatures of the main steam and reheated steam might decrease if a large amount of solar thermal energy was introduced, thereby threatening the safety of the boiler operation [25,26]. Thus, the boiler should not be regarded as a black box, and calculations for inner heat transfer process and the safe operation of the boiler should be taken into account.

In a coal-fired power plant, steam is extracted from turbines to heat feedwater in stages, thereby increasing the inlet feedwater temperature in the boiler and the thermal efficiency of the entire power plant [27]. Coal consumption can be reduced and efficiency can be increased through solar energy input if the integration configuration can achieve a high inlet feedwater temperature. This study developed a new feedwater heating pattern. In this system, a solar HP feedwater heater H0 is added to heat the inlet feedwater of the boiler. The extraction steam is not replaced by solar heat. Instead, the solar heat is designed to further enhance the temperature of inlet feedwater. The new solar HP feedwater heater H0 will improve the operation performance of the SACFPP. An issue that will be determined is what happens when solar energy is used to enhance inlet feedwater temperature. An assessment is conducted to verify the safety and efficiency of this new SACFPP system.

In this paper, a creative solar thermal integration of the boiler of CFPP is studied. A solar high-pressure feedwater heater H0 is used to heat the inlet feedwater to further enhance its temperature. A 600 MW coal-fired supercritical power plant is selected as a case study. An all-condition mechanism model (ACMM) of SACFPP is proposed and simulated by MATLAB/Simulink. The energy transfer submodels for each exchanger of the boiler are developed. The maximum solar energy absorption is determined to ensure the safe operation of the boiler. Thermodynamic economy analyses are also conducted by using different solar energy inputs.

2. System description

Fig. 1 presents the SACFPP. The SACFPP system includes two subsystems: a coal-fired power plant and a solar collector field. The boiler used in CFPP is a 600 MW supercritical once-through boiler, and turbines are N600-24.2/566/566. Three high-pressure feedwater heaters (H1, H2, and H3), a deaerator (H4), and four low-pressure feedwater heaters (H5, H6, H7, and H8) are used. Hypothetically, a solar high-pressure feedwater heater H0 is located between high-pressure feedwater heater H1 and the economizer. The hybridization strategy of SACFPP uses the solar heat carried by solar salt (40%KNO_3-60%$NaNO_3$) from the solar collector field to heat the outlet feedwater of H1 through H0, which improves the inlet feedwater temperature of the boiler to decrease the coal consumption of CFPP [26].

3. Modeling the SACFPP system

3.1. All-condition mechanism model for SACFPP

An ACMM of SACFPP is shown in Fig. 2. The SACFPP system comprises the boiler, turbines, feedwater heaters, the condenser, the digital electric hydraulic control system, and other equipment. MATLAB/Simulink is used to develop the mechanism model of SACFPP by using the modularization method. The system configuration, operation strategy, and coupling performance are analyzed with an off-design condition. Variable operation parameters under different load and boundary conditions are used for ACMM by coupling iterative