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Research Paper

Coupling performance analysis of a solar aided coal-fired power plant

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HIGHLIGHTS

- An all-condition mechanism model (ACMM) of SACFPP is proposed.
- The coupling analysis of working fluid (steam/water) in SACFPP are discussed.
- The hybridization of SACFPP optimizes.
- The output power shock of SACFPP caused by DNI is assessed.

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ABSTRACT

Coal-fired power plants are the dominant form for power generation in many countries, even though they are the main contributor to the current environmental crises. The solar aided coal-fired power plant is an attractive new way to reduce the coal consumption by using solar energy. From the perspective of operational mechanism and coupling property, an all-condition mechanism model of the solar aided coal-fired power plant is proposed in this paper. The operation of an N600-24.2/566/566 supercritical coal-fired power plant hybridized with parabolic trough solar collectors is simulated using Matlab/Simulink in the fuel saving mode. And a new evaluation index of solar energy is proposed to reasonably assess solar energy contribution to the solar aided coal-fired power plant. When the solar steam is used to replace the extraction steam in the feedwater heating system, the change of the main steam, the reheat steam, and the extraction steam are discussed as the coupling property is taken into account. Furthermore, thermal economic analysis is carried out to optimize the solar steam replacement and the entrance of inlet feedwater to the solar field. Moreover, the efficiency and output power of the high pressure cylinder, the intermediate pressure cylinder, and the low pressure cylinder are discussed when the extraction steam is replaced by the solar steam in the feedwater heating system. Finally, the output power shock of the solar aided coal-fired power plant caused by the fluctuation of Direct Normal Irradiance is assessed. It is found that the strong fluctuation of Direct Normal Irradiance affects the power quality of the solar aided coal-fired power plant significantly.

1. Introduction

The fast growing economy in China results in large energy demand. According to the statistical data from National Energy Administration of China, China's coal consumption in 2014 was 2.81 billion tons, comprising 66.0% of the total, as well as 4233.73 TW h of thermal power generation, accounting for 74.9% of the total. The pollutions released during the burning process of coal lead to serious environmental problems. The serious haze over a wide area of China in the winter of 2015 was largely due to the intensive use of coal. Thus, it is imperative for China to develop clean renewable energy to reduce the use of coal.

Solar energy is one of the most potential renewable energies [1,2], while annual total solar radiations in most areas in China are more than 4000 MJ m^{-2} and some places even over 6000 MJ m^{-2}, such as Tibet, Xinjiang, Gansu, and Inner Mongolia. However, traditional stand-alone solar plants (SASP) are difficult to be used widely in China for the low efficiency, large area occupied, and high cost. The solar energy for generation is not currently competitive with the conventional fossil power generation [3]. Hybridization seems to be an attractive option for China at present, which integrates both solar energy and coal concurrently to not only overcome the problems of the traditional SASP, but also decrease the coal consumption in the traditional coal-fired power plants (CFPP).

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Nomenclature

b	coal consumption rate (kg kW^{-1} h^{-1})
B	coal consumption (kg)
D	mass flow (kg s^{-1})
DNI	Direct Normal Irradiance (W m^{-2})
p	pressure (MPa)
P	power output (kW)
Q	heat capacity (kJ)
q_{net}	low heat value of the standard coal (kJ kg^{-1})
t	temperature (°C)
Δb	coal saving rate

Greek symbols

η_b	efficiency of the boiler
η_{sol_el}	solar-electricity efficiency

Acronyms

ACMM	all-condition mechanism model
BFPT	boiler feed water pump turbine
C	condenser
CFPP	coal-fired power plants
CP	condensate pump
CSP	concentrated solar power
DEH	digital electric hydraulic control system
ES	extraction steam
ESV	exhaust steam valve
FP	feedwater pump
FWH	feedwater heater
H*i*	the *i*th feedwater heater
HP	high pressure
ICP	inter-connecting pipe
IP	intermediate pressure
IPGV	intermediate pressure governing valve
IPMV	intermediate pressure main stop valve
LP	low pressure
OP	oil circulating pump
OWHE	oil-water heat exchanger
SA	saturation
SACFPP	solar aided coal-fired power plant
SAFH	solar-aided feedwater heating
SASP	stand-alone solar plants
SOL	solar steam
SSLH	shaft seal leakage heater
THA	turbine heat acceptance
RS	regulation stage
TS	turbine stage

Subscripts

con	condensing
fw	feedwater
g	gas
in	inlet
out	outlet
s	steam
sol	solar
suc	subcooling
suh	superheating

There are two main ways to hybridize solar energy with the fossil. One is taking solar energy as the dominated energy while the fossil is used to keep the system stable, and the other way is to use the fossil as the main energy while solar energy is the auxiliary thermal source [4]. The early work of hybridization was conducted by Zoschak in 1975 to study different ways of putting solar thermal into an 800 MW fossil power plant [5]. Hybridization systems are gaining interest in recent years.

The system integration scheme is one of the main subjects in the field. Williams compared four hybridizations of solar thermal power, including redundant system hybridization, parallel fossil heater hybridization, solar augmented hybridization and solar preheat hybridization. He pointed out that well-designed hybrid plants can improve energy conversion efficiency and reduce capital investment [6]. Jun analyzed two integration types of solar aided coal-fired power plant (SACFPP), it was reported that the solar thermal integration before economizer achieved higher efficiency than the latter [7]. Another study found the most efficient way to make use of the medium and low temperature solar thermal was to replace the bled-off steam in the regenerative system [8]. It is concluded that the most attractive integration was the highest possible pressure feedwater heater being replaced by the solar energy [9]. Moreover, different concentrated solar power (CSP) technologies to hybridize with power plants were discussed. It seemed the Fresnel system may be the best possible technology for feedwater heating in the hybridization system [10]. SAPG with non-concentrating collectors seemed to gain higher net solar efficiencies and cost-effective than that with concentrating collectors on the per unit land area basis [11]. In addition, solar assisted post-combustion CO_2 capture of power plants emerges recently [12].

In operation characteristics, Yan calculated that the maximal solar efficiency was 45% when the solar heat with a temperature of 330 °C replaced high pressure heaters [13]. The study of integration with the solar-aided feedwater heating (SAFH) indicated that the larger the power plant, the higher the benefit [14]. Hou's results showed the higher solar-electric efficiency was 26.16% [15]. The researches indicated the thermal-electric efficiency of SAFH was over 35% based on the assumption that the state of working fluid at every point of the system does not change with or without SAFH [16,17], but the thermal efficiency of solar energy was 30.12% when the flow rate change was considered [18]. The effects of the solar irradiation intensity, the incident angle, the flow rate of thermal oil on the performance of the solar-electricity efficiency for a SACFPP under off-design conditions were also analyzed [19]. Wu concluded that the thermal energy storage system increased both of the annual solar generation and the annual solar-electricity efficiency performance of the SACPG system, and proposed a balance point for thermal energy storage hours and solar field cost [20].

It has been demonstrated by some authors that the solar thermal efficiency of SACFPP was higher than that in SASP. Gupta analyzed exergy characteristics for different components of a SASP and concluded that SACFPP was more advantageous than SASP [21]. Pierce found that the annual electricity generated from solar thermal at SACFPP was more than 25% higher than that at a similar-sized SASP in the same condition [22].

Moreover, thermodynamic and exergy evaluation are also studied in some researches. Suresh analyzed the energy, exergy, economic, environmental impacts of SACFPP, and established the technoeconomic viability, it was shown that the instantaneous fuel conservation was about 5–6% with the substitution of turbine bleed streams to feedwater heaters [23]. Zhai took the amount of coal saving in solar unit investment per hour as the evaluation criteria for SACFPP [24], and it was revealed the thermo-economic cost of solar energy increased by 16.9–21.6% because of its large investment and low efficiency based on the analysis of