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A novel flue gas waste heat recovery system for coal-fired ultra-supercritical power plants

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HIGHLIGHTS

- A novel waste heat recovery system is proposed in this paper.
- Energy, exergy and techno-economic analysis are quantitatively conducted.
- Better energy-savings of the proposed WHRS is obtained through system integration.
- Lower exergy destruction is achieved in the proposed WHRS.
- Greater economic benefits have been found in the proposed WHRS.

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ABSTRACT

Recovering flue gas waste heat is important in improving power plant efficiency. The most widely method is installing a low-temperature economizer (LTE) after the electrostatic precipitator (ESP) to heat the condensed water, thereby saving the extraction steam from the steam turbine and achieving extra work. The inlet flue gas temperature of the LTE is relatively low, so it can only heat condensed water from low-grade regenerative heaters, resulting in comparatively minor energy savings. After conducting an in-depth analysis of the conventional waste heat recovery system (WHRS), this paper proposes a novel WHRS, in which the air preheater is divided into high-temperature (HT) and low-temperature (LT) air preheaters, and the LTE can be situated between the ESP and the LT air preheater. Through system integration, higher-grade extraction steam can be saved, resulting in greater economic benefits. Results show that the net additional power output can reach 9.00 MW_e and using the proposed WHRS can yield net benefits up to USD 2.60 million per year, which is much greater than those of conventional WHRS. Exergy destruction is also reduced from 34.1 MW_{th} in the conventional WHRS to 28.5 MW_{th} in the proposed WHRS.

1. Introduction

In China, coal-fired power plants consume nearly half of all available coal, and the resulting CO_2 emissions account for over 40% of the total nationwide emissions. Therefore, energy conservation in coal-fired power plants is important to China's energy security and programs for greenhouse gas control.

Currently, exhaust gas temperature can reach 120 °C–140 °C or even higher [1,2]. The thermal energy of exhaust flue gas dumped into the environment accounts for approximately 50%–80% of a boiler's thermal loss, and 3%–8% of the plant total energy input. Obviously, there exists a great potential to improve the efficiency of the power plant by the recovery of the waste heat of the flue gas [3,4].

The most widely used method of flue gas heat recovery is installing an auxiliary heat transfer surface, referred to as a low-temperature economizer (LTE), downstream of the electrostatic precipitator (ESP) to heat a portion of the condensed water. It is well known that, the condensed water is recycled back into the boiler as feed water at temperature ranging from 250 °C to 300 °C after multistage preheating using steam extracted from different levels in the regenerative heating system. This process is a remarkable energy conservation concept that is widely applied in existing power plants. For the LTE, all the heat needed for

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Nomenclature

Abbreviation

SG	steam generator
HPT	high-pressure turbine
IPT	intermediate-pressure turbine
LPT	low-pressure turbine
COND	condenser
FWP	feed water pump
CP	condenser pump
EG	electric generator
LTE	low-temperature economizer
WHRS	waste heat recovery system
GTI	Gas Technology Institute
US	The United States
USC	ultra-supercritical
LHV	low heat value
DEA	deaerator
RH	regenerative heater
ESP	electrostatic precipitator
NAR	net annual revenues
O&M	operation and maintenance

Symbols

ΔP_t	work output increment, (MW_e)
ΔP_f	increase in draft fan power, (kW)
Δp_r	increase in flue gas resistance, (Pa)
η_f	induced draft fan efficiency (%)
D	volume flow of flue gas, (m^3/s)
ΔP	net increase in work output, (MW_e)
q	heat rate of the power plant, (kJ/kWh)
E_{total}	net input of power unit, (MW_{th})
P_{net}	net power output, (MW_e)
A	energy level
$\Delta\varepsilon$	exergy change, (kJ/kg)
ΔH	energy change, (kJ/kg)
ΔS	entropy change, (kJ/(kg °C))
T_0	environmental temperature, (°C)
EAI	extra annual income, (million USD)
C_e	on-grid power tariff, (USD/kWh)
h_{eq}	the equivalent operation per year, (h/year)
TIC	total investment capital, (million USD)
f_M	material correction factor
f_P	process pressure correction factor
f_T	process temperature correction factor
$f_{M\&S}$	Marshall and Swift index
S	scale parameter, (m)
b	scale factor
i	fraction interest rate per year,(%)
n	number of years
r	reference

preheating the condensed water originates from the flue gas, instead of the extraction steam, which can save a portion of the extraction steam from the steam turbine. The saved steam is able to pass through the following stages of the steam turbine and continues to expand for more power output, accompanied by improved net power plant efficiency.

Currently, the use of the flue gas waste heat is becoming a hot topic both in the industrial community and technological research. In Germany, the Schwarze Pumpe power plant with a 2 × 800 MW lignite generation unit uses a flue gas division system after the ESP, and uses exhaust energy to heat the condensed water [5]. In China, the Shanghai Waigaoqiao No. 3 power plant uses condensed water at the entrance of the 7th-stage low-pressure regenerative heater (RH) to retrieve heat energy from flue gas in the LTE located after the ESP: this system reduces the design temperature of the flue gas from 125 °C to 85 °C, which improves boiler efficiency 2%-points and overall unit efficiency by 0.8–0.9%-points [6].

Studies have also examined the structure and materials of heat exchangers of used in waste heat recovery system (WHRS). More specific, Zhao et al. [6] conducted a study on using LTE with spiral-finned tubes for waste heat recovery and the ash deposition flow characteristics of flue gas spiral finned tube economizers. The LTE structure is comprehensively optimized in this paper. Chen et al. [7] investigated technologies for exploiting the large amount of low-grade heat available from flue gas through industrial condensing boilers, and recover the latent heat of water vapor in flue gas. The Gas Technology Institute (GTI) in the United States investigated the use of transport membrane condenser technology to recover water and latent heat in the exhaust gas and conducted a series of industrial tests and commercial projects under the United States Department of Energy [2]. Plastic heat exchangers were used to cool flue gas temperature down to 50 °C. However, the low heat transfer coefficient of plastic LTE requires a large heat exchanger size, which is not widely applicable to large-scale power plants. As for the thermodynamic and economic analysis, Wang [8] demonstrated the energy-saving principles of the LTE using the equivalent enthalpy drop method, which is commonly used to estimate the off-design performance of steam turbines. Espatolero et al. [3] compared various WHRS configurations by the thermodynamic and economic analysis: an indirect WHRS in the bypass flue gains the best energy savings, increasing efficiency by 1.11% above the reference case. However, the configuration of this arrangement is rather complex, which will enhance the system complexity and reduce the cost-competitiveness of the WHRS. The techno-economic performance of alternative RH configurations in the WHRS has been compared in the literature [9]. However, these studies focused on optimizing LTE configuration in the condensed water side, the characteristics of the LTE arrangement in the flue duct were not considered.

The preliminary study and demonstration projects showed the characteristics of the WHRS, including the structural characteristic of the LTE and the energy-saving calculation of the WHRS. A number of valuable achievements have been made. The feasibility of flue gas waste heat recovery was confirmed by techno-economic analysis and the anti-corrosion material technology was also been further developed.

However, comprehensive system optimization of WHRS has not received full attention, because of the relatively mature application in existing projects nowadays. Methodologies for thermodynamic analysis are based on the first law of thermodynamics, and the exergy analysis of the WHRS is being disregarded. In fact, WHRS performance can be improved by the process optimization and system integration on the level of the whole tail heating surfaces in the boiler through relatively simple retrofitting. Thus, integrated analysis and system optimization of the tail heating surfaces, rather than focusing on the LTE itself, should be prioritized. Additionally, the exergy analysis of the WHRS is indispensable to determining the energy-saving mechanism of WHRS.

In view of this, based on the in-depth analysis of conventional WHRS, we propose a novel WHRS, coupled with comprehensive