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A novel cascade energy utilization to improve efficiency of double reheat cycle

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ABSTRACT

Large mean terminal temperature difference of conventional regenerative air heater and high superheat degree of bleeding steams are the bottleneck of conventional steam rankine cycle, which limits the cycle for further efficiency improvement. In this study, a state-of-the-art double reheat power plant is selected as the reference cycle. A novel cycle covering steam, water and air process is invented based on the systematic combination of flue gas heat recovery and bleeding steam cascade energy utilization.

Thermodynamic model is developed to analyze the performance improvement and exergy method is applied to validate and identify the cycle thermodynamic efficiency advantage. Simulation result presents novel cycle net heat rate is improved by 104.8 kJ/kWh and cycle net efficiency is increased by 0.61%. Feed water pump turbine inlet steam connection optimization accounts for 14 kJ/kWh net heat rate benefits for the novel cycle. Feasibility study proves it is possible to implement the novel cycle in a newly planned power plant. Based on techno-economic analysis, it is found that the total investment capital of novel cycle is 7.44 million US dollars and net annual revenue is 0.59 million US dollars compared with the reference cycle. Static capital investment paid back period is expected within 15 years in a newly planned power plant.

1. Introduction

IEA reported global coal demand fell by 1.9% and dropped for a second year in a row in 2016 [1]. For instance, fossil fuel power generation still dominates in china's energy structure and accounted 57% of total power capacity by the end of 2016, but it has fallen by 15% in the past decade [2]. With the prosperous development of renewables and stringent environment requirements, fossil fuel power generation is in a dilemma either fading out or striving to improve cycle efficiency. Application of nickel base alloy material into A-USC power generation for elevating cycle initial parameters is an optional technology, but it still has a long way to be widely implemented. Current advanced ultra supercritical (A-USC) power generation technology provides the last hope for mitigating environment pressure and improving efficiency of power production before the fossil fuel fades out in the coming few decades.

Flue gas waste heat utilization is an effective approach to improve the efficiency of fossil fuel power plant. Xu et al. [3] developed thermodynamic models to analyze four schemes of waste heat exchanger utilizing boiler exhaust flue gas. The waste heat exchanger heats up the condensate water, then consequently reduced the low pressure turbine extraction steam which results in turbine power output increment and cycle efficiency improvement. Stevanovic et al. [4] reported USC lignite power plant Niederaussem unit K applied an innovative flue gas heat recovery system which breaks the heat utilization boundary barrier of boiler and turbine. The innovative system is composed of an air heater bypass flue gas duct, a plastic low temperature economizer arranged at the upstream of the FGD, a high pressure economizer and a low pressure economizer installed in the bypass flue gas duct. The high pressure economizer and low pressure economizer heats the feed water and condensate water from turbine steam water cycle which replaces the regenerative bleeding steam with boiler flue gas energy and increase the turbine shaft output. In addition, a huge plastic economizer installed at the upstream of FGD is designed to compensate the bypassed flue gas energy to heat up the cold air. This innovative flue gas heat recovery system increase the cycle efficiency by 0.9%. Similar flue gas bypass system simulation research was also reported in [5,6] with standard coal consumption decrement of 4.0 g/kWh, 5.38 g/kWh respectively. Espatolero et al. [7] conducted a research on increasing power plant output and net efficiency with the integration of boiler cold

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Nomenclature

A-USC	advanced ultra supercritical
FGD	flue gas desulphurization
HPH	high pressure heater
LPH	low pressure heater
BS	bleeding steam
FGHRS	flue gas heat recovery system
PA	primary air
SA	secondary air
THA	turbine heat acceptance condition
SLT	second law of thermodynamics
DTM	mean log terminal temperature difference
DTLO	lower terminal temperature difference
DTUP	upper terminal temperature difference
AH	air heater
ORC	organic rankine cycle
S-CO_2	supercritical carbon dioxide
TIC	total investment capital
EAI	extra annual income
CRF	capital recovery factor

Greek symbols

$\in$	effectiveness of a heat exchanger
ε	exergy efficiency
$\varkappa$	discount rate
Δ	changeable quantity

Mathematical symbols

$\dot{m}$	mass flow of fluid, kg/s
C	heat capacity of fluid, kJ/kg K
A	heat transfer area, m^2
Q	transferred heat, MW
W	heat capacity rate of fluid, MW/K
$\dot{E}$	physical exergy, MW
h	specific enthalpy, kJ/kg
T	temperature, °C
s	specific entropy, kJ/kg
n	service life of equipment
r	interest rate
k	heat transfer coefficient, $W/m^2 K$

Subscripts and superscripts

max	maximum
min	minimum
h	hot fluid
c	cold fluid
i	inlet
o	outlet
$O\&M$	operation and maintenance
k	the kth component
D	exergy destruction
P	exergy production
F	fuel exergy

end and steam water cycle. Simulation results show a 0.5% cycle efficiency point is achieved by an indirect FGHRS with two (LP and HP) feedwater heaters system.

In addition to flue gas waste heat utilization, a large amount of researches have focused on novel system design and cycle integration. Organic rankine cycle (ORC) and thermoelectric combined with conventional steam rankine cycle demonstrates potential cascade energy utilization. Ziółkowski et al. [8,9] studied different schemes of ORC combined with supercritical steam power plant, heat sources of ORC are supplied by boiler exhaust gas, rejected heat of condenser and bleeding steam. Yazawa et al. [10,11] reported thermoelectric topping generator applied in boiler furnace to minimize the exergy loss due to large temperature gradient distribution and contribute to 6% overall efficiency improvement. Supercritical carbon dioxide (S-CO_2) brayton cycle applied in coal fired power plant is another hot research area. Power generation efficiency of different scheme developed by EDF [12] and IAE [13] are reported to be more than 47.8%. Liu et al [14] proposed a novel S-CO_2 cycle integrated with coal fired power plant, part of the flue gas before regenerative air heater provide the heat source for S-CO_2. By means of optimization, coal consumption rate of the whole plant decreased by 3.8 g/kWh. Xu et al. [15] investigated a novel partial-subsidence tower-type boiler design in USC power plant which expects to arrange the boiler 1/2–1/3 of boiler height is embedded underground and then significantly reduce the length of steam pipelines. Thermodynamic performance simulation reveals that partial-subsidence tower-type boiler design has a more advantage on pipeline pressure loss compared with conventional tower boiler and results in 0.1% increment of cycle efficiency. Kjaer et al. [16,17] proposed a master cycle which employs a tuning turbine to effectively utilize the superheat of bleeding steam of USC double reheat unit. Part of the exhaust steam from the high-pressure (HP) turbine flows into a tuning turbine and tuning turbine has several bleeding steams to feed regenerative heater and deaerator to replace the bleeding steam from intermediate pressure turbine. The superheat of bleeding steam will be significantly reduced by this design and contribute to 3.5% heat rate improvement compared with a conventional single reheat cycle. Regenerative heater arrangement optimization is generally regarded as effective way to improve cycle efficiency. Espatolero et al. [18] presented a study of efficiency improvement strategies for the feed water heaters network designing in supercritical coal-fired power plants which analyzes the best available technology for supercritical steam cycle. By means of thermodynamic simulation, different strategy is analyzed based on numbers and location of drain pumps and numbers of regenerative heaters. Conclusions show a feasible improvement of the overall plant efficiency of 0.7% in comparison with state-of-the-art reference plant.

Meanwhile, researches on conventional steam water cycle have effectively increased the efficiency of coal-fired power plants. Li et al. [19] investigated the partial load performance advantage by adding a No.0 high pressure heater to turbine regenerative system, operation and simulation results indicate coal consumption rate decreased by 0.42 g/kWh. Fu et al. [20] analyzed various measures for increasing the thermal efficiency and the corresponding improvement potential according to the exergy analysis method. Zhou et al. [21] applied parametric analysis and process optimization of a double reheat cycle. Simulation results proved ten-stage of regenerative heaters has 0.49% efficiency advantage compared with eight-stage configuration. A theoretical investigation of the principles of energy efficiency improvement in coal-fired power plants by removing a portion of the coal moisture content was performed [22]. Net efficiency of the power plant increase in the range of 0.6–0.9% as well as boiler efficiency increase 0.4–0.5%.

However, few researches have been reported on systematic efficiency improvement of double reheat cycle. This paper selects a state-of-the-art double reheat power plant as reference cycle. A novel cycle covering steam, water and air process is invented based on the systematic combination of flue gas heat recovery and bleeding steam cascade energy utilization. Thermodynamic model is developed to analyze and reveal the performance improvement based on a novel cycle. Thermodynamic model is developed to analyze the performance