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Exergy analysis of a 1000 MW double reheat ultra-supercritical power plant

Ningning Si [a], Zhigang Zhao [a,b], Sheng Su [a,*], Pengshuai Han [a], Zhijun Sun [a], Jun Xu [a], Xiaoning Cui [a], Song Hu [a], Yi Wang [a], Long Jiang [a], Yingbiao Zhou [a], Gang Chen [a], Jun Xiang [a,*]

[a] State Key Laboratory of Coal Combustion, School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[b] Shenhua Guohua Guangtou (Beihai) Power Generation Co., Ltd., Beihai 536000, China

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ABSTRACT

This study evaluates the performance of a 1000 MW double reheat ultra-supercritical power plant. An exergy analysis was performed to direct the energy loss distribution of this system. Based on the exergy balance equation, together with exergy efficiency, exergy loss coefficient, and exergy loss rate, the exergy distribution and efficiency of the unit were determined. Results show that the highest exergy loss in furnace is as high as 85%, which caused by the combustion of fuel and heat exchange of water wall. The VHP and the two LPs suffer the highest exergy losses, namely 1.86%, 2.04% and 2.13% respectively. The regenerative heating system has an exergy loss rate of 2.3%. The condenser suffers a heat loss of 999 MW, but its exergy is as low as 20.49 MW. The sensitivity variations of the unit's exergy efficiency with load, feedwater temperature, main steam temperature and pressure, the twice reheat steam temperatures, and steam exhaust pressure were also analyzed, indicating that load, feedwater temperature, and steam exhaust pressure influence the exergy efficiency of this unit than other elements. The overall exergy efficiency decreases along with the gradual increase of steam exhaust pressure at any constant outlet boiler temperature, but it increases as the load, feedwater temperature, main steam temperature and pressure, and twice reheat steam temperatures increase at fixed steam exhaust pressure.

1. Introduction

Considering today's increasingly serious environmental problems, along with the depleting primary energy resources in the world, developing large-capacity, high-parameter, low-pollution, and remarkably efficient coal-fired power generation techniques to increase unit efficiency is the most feasible means to save energy [1]. To increase the efficiency of a power unit, many techniques are employed. The development of the advanced ultra-supercritical technologies is the subject of European, Japanese, American and Chinese project (AD700 project), which aims at a completive power plant and the live steam parameters can reach to 35 MPa/700 °C and the net efficiency exceeding 50% [2], but due to the material problem the achievement of the project is postponed to 2020. Therefore, at present the most remarkable method is the double reheat ultra-supercritical (USC) technique, which increases efficiency by using large-unit capacity and high steam parameters [3]. High-parameter double reheat USC unit is a new generation of USC units that can be ranked between the existing USC unit and the European Union-financed AD700 project [4]. In recent years, a number of large USC units with up to 1000 MW capacities are widely applied. The success of such USC unit has exhibited its superiority, thereby enabling the development of double reheat USC unit. Double reheat can increase efficiency by raising the average temperature of the heat exchange and steam parameters at turbine inlet, so provides great potential to do work and fulfills the exhaust steam humidity requirement of turbine exhaust [5]. Typical double-reheat USC power plants, i.e., Kawagoe Power Plant in Japan and Nordjylland Power Plant in Denmark, can reach a thermal efficiency of over 45% on a low heat value basis [6]. A 1000 MW double reheat USC unit has been built and operated successfully in 2015 in Taizhou Power Plant in China with the main steam parameter of 31 MPa/600 °C/620 °C/620 °C. Therefore, it becomes the first 1000 MW double reheat USC power plant in the world. The Huaneng Anyuan (660 MW, 32.45 MPa/605 °C/623 °C/623 °C) and Laiwu (1000 MW, 31 MPa/600 °C/620 °C/620 °C) Power Generation Plants have also built double reheat USC units in 2012. These units started operation in 2015. The Huadian Jurong Power Generation Plant

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* Corresponding authors.
E-mail address: susheng_sklcc@hotmail.com (S. Su).

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Nomenclature

TMCR	turbine maximum continuous rating
W	non-isentropic expansion output power (kW)
θ_s	isentropic efficiency
θ_m	mechanical efficiency
m	mass flow rate (kg/s)
Δh_s	specific isentropic enthalpy drop (kJ/kg)
e	specific exergy (kJ/kg)
Δe_l	exergy loss
Δe_{li}	amount of exergy loss of the heat subsystem
Δs	entropy created in the system (kJ/kg·K)
T_0	previously defined reference temperature (K)
s	specific entropy (kJ/kg·K)
h	specific enthalpy (kJ/kg)
w	specific work (kJ/kg)
e_g	exergy gain
e_c	exergy cost
ξ_e	exergy loss coefficient
ζ_{ei}	exergy loss rate
η_e	exergy efficiency
q	specific heat transfer (kJ/kg)

Subscript

in	parameters in the system
out	parameters out of the system

(*Fig. 2*)

De	decomposer
Com	combustor
Sep	separator
Fs	splitter
Ap	air preheater
Ww	water wall
Ltfr	low-temperature first reheater
Eco	economizer
Q-gas	heat released into the environment
Lts	low-temperature superheater
Hts	high-temperature superheater
Csf	cold segment of high-temperature first reheater
Css	cold segment of high-temperature second reheater
Hsf	hot segment of high-temperature first reheater
Hss	hot segment of high-temperature second reheater
Ltsr	low-temperature second reheater

(*Fig. 3*)

VHP	very high pressure cylinder
HP	high pressure cylinder
IP	intermediate pressure cylinder
LP1	No. 1 low pressure cylinder
LP2	No. 2 low pressure cylinder
Rh1	the first reheater
Rh2	the second reheater
Con	condenser
supsteam	superheated steam
l	left side
r	right side
Out1	No. 1 outer steam cooler
Out2	No. 2 outer steam cooler
E-t	external steam turbine
HRH	high pressure regenerative heater
LRH	low pressure regenerative heater
H	heater
DEA	deaerator
fewater	feed water
c	cold side
h	hot side

and the Shenhua Guohua Beihai Power Plant are currently building units to add to the growing list of double reheat USC units in China.

Rashidi et al. [5] studied that the efficiency of double reheat power plant can be theoretically increased by 1.0–2.0% than that of single reheat unit. Many research institutions and universities delved into the research on the double reheat USC unit in China, focusing on the challenging issues on boiler and turbine matching, steam and water parameter characteristics, and boiler design. Zhou et al. [6] showed that the power generation efficiency of the double reheat power plant could increase by 0.49% through parametric and process optimizations. Sha et al. [7] investigated the causes and influencing factors of jet deviation in the dual-circle tangential firing single-furnace USC boiler. Yan et al. [8] proposed a local method for quantitatively analyzing the cost-effectiveness of the double reheat USC unit based on equivalent heat drop theory as well as strict mathematical analysis and theoretical inference.

The 1000 MW double reheat USC units remain in the early stages of engineering applications. Dual reheaters are added into the boiler, as a result, the corresponding structure and arrangement of the heating surface changed considerably. The distribution of thermal energy, heat transfer performance of boiler heating surface, and operation performance testing and optimization remain absent. In a double reheat turbine system, a very high pressure turbine (VHP) and two external steam coolers are added, and extraction stages and points are changed. The corresponding energy distribution and thermal efficiency of each device also changed greatly. The energy distribution of the whole system, heat transfer performance of the furnace, and heat recovery performance of heaters should be studied by using thermodynamics method.

Most of the aforementioned works relied on heat balance analysis based on the first law of thermodynamics, namely energy-based methods. In this method, all forms of energy are considered to be equivalent. Energy flows into and out of a system along with different paths of mass flow, heat transfer, and work, the loss of quality of energy is not taken into account [9]. These studies based on the energy-based methods are easy to understand, but only the quantitative variation of energy is considered and its qualitative variation is disregard. Therefore, the application of such a method for assessing the improvement possibilities of a process can result in a distorted vision of researched system and the irreversibility of processes within the system cannot be characterized [10,11]. Also, these works overemphasize the thermodynamic cycle of the turbine and the loss of the condenser, but disregard energy-level matching and irreversible energy loss. By contrast, exergy analysis can characterize the work potential of a system. Exergy is defined as the maximum theoretical useful work obtained with the reference or dead state [12–14]. Exergy analysis based on the second law of thermodynamics can accurately show the maturity and utilization of a device. Ege et al. [15] studied the uncertainties of a large scale lignite fired power plant cycle and various measurement parameter sensitivities for different design power outputs using a black box method based on the exergy analysis, and found that LHV determination was the most important uncertainty source of energy and exergy efficiency. Aljundi, Regulagadda