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Optimum superheat utilization of extraction steam in double reheat ultra-supercritical power plants ☆

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HIGHLIGHTS

- Two superheat utilization schemes of extraction steam are proposed.
- A comparative study of thermodynamic and techno-economic analyses is conducted.
- Two proposed schemes can both effectively utilize the superheat of extraction steam.
- More obvious energy saving effect is obtained at low load conditions.

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ABSTRACT

Double reheat ultra-supercritical power plants have been receiving an increasing amount of attention because of their high thermal efficiency. However, the superheat degree of extraction steam in double reheat power plants is relatively high and results in a large temperature difference in the heat transfer process of the regenerative system. As a result, this impedes further improvement of the thermal efficiency of double reheat power plants. This paper presents two superheat utilization schemes of extraction steam in a double reheat ultra-supercritical power plant, where one scheme adopts outer steam coolers and the other employs a regenerative turbine. A comparative study of the two proposed schemes is conducted. Thermodynamic and techno-economic analyses are performed to reveal the energy saving effects of the proposed schemes. Thermodynamic analyses under partial load operation conditions are also presented. The results reveal the following. The power generation efficiency of the outer steam cooler scheme and the regenerative turbine scheme increases by 0.16 percentage points and 0.67 percentage points compared with a reference double reheat power plant, respectively. When the load is reduced, the energy saving effects of the proposed schemes become more obvious. The power generation efficiency increments of the outer steam cooler and the regenerative turbine schemes can reach 0.19 and 0.79 percentage points, respectively, at a 50% turbine heat acceptance load. The net annual revenues of the two schemes are 0.29 and 1.59 million USD, respectively. The results indicate that the two proposed schemes can both effectively utilize the superheat of extraction steam for double reheat ultra-supercritical power plants. In comparison, the regenerative turbine scheme is superior to the outer steam cooler scheme in terms of thermodynamic and techno-economic performance.

1. Introduction

Coal plays the dominant role in power generation in China. According to statistics, pulverized coal-fired power plants provide nearly 80% of the country's total electricity requirements [1]. These power plants account for more than half of the total national coal consumption and subsequently contribute nearly 50%, 37%, 33% and 50% to the total SO_x, NO_x, dust and CO_2 emission volumes, respectively, for the entire country [2,3]. Moreover, China has been the world's largest producer and consumer of energy since 2013 [4]. As a result, energy conservation is extremely significant to energy security, environment protection and emission reduction in China. Power plants should operate at a high parameter condition in supercritical (SC) and ultra-supercritical (USC) domains to accomplish this goal. Power plant parameters have been enhanced extremely over the past few decades. Live steam pressure can reach 30 MPa and live steam temperature has increased to 600 °C

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Nomenclature

Abbreviation

SC	supercritical
USC	ultra-supercritical
HP	high-pressure
IP	intermediate-pressure
LP	low-pressure
LHV	low heat value
DEA	deaerator
CON	condenser
RH	regenerative heater
GEN	generator
THA	turbine heat acceptance
TIC	total investment capital (million USD)
O&M	operation and maintenance
EAI	extra annual income (million USD)
NAR	net annual revenue (million USD)

Symbols

η	power generation efficiency (%)
q	heat consumption rate (kJ/kW h)
k	discounted rate (%)
n	service life of equipment (years)

[5]. Current boiler thermal efficiency ranges from 93% to 95% and the isotropic efficiency of steam turbines has reached an average of above 90% in USC power plants [6]. A recent study has reported that the highest thermal efficiency of 46.5% has been achieved by the Shanghai Waigaoqiao power plant [7]. Currently, the parameters of power plants under construction are all in the USC domains. Many technologies are utilized to further increase the efficiency of the steam/water cycle. Reheat technology is one of the most outstanding examples, which improves efficiency by increasing the mean temperature of the endothermic process [8]. Double reheat technology has been employed in several power plants and has gained preferable thermal performances. Typical double reheat power plants include the Manham power plant in Germany and the Nordjylland power plant in Denmark, both with a thermal efficiency over 45% [9,10]. Double reheat technology has attracted considerable attention over the past few decades. Rashidi et al. [11] studied on the thermodynamic analysis of a steam power plant using double reheat technology, and evaluated the main parameters for the steam cycle. Li et al. [12] proposed a heat circulation calculation model for the thermal system of double reheat power plants. Yan et al. [13] presented a detailed mathematical model and conducted a thermodynamic analysis of double reheat systems. Reddy et al. [14] investigated the selection of appropriate reheat parameters for double reheat power plants. Double reheat USC power plants have been identified as the key research and development project of the National "Twelfth Five-Year Plan" of the Chinese government [15].

Given that the live steam parameters of USC power plants have advanced rapidly in recent years, the parameters of the extraction steam have also correspondingly increase, resulting in a highly superheated extraction steam. Berg [16] investigated the theoretical and practical advantages obtained by the adoption of high steam parameters and reheat technology. The superheat degree of the extraction steam in double reheat power plants is even higher because of the two-stage reheat process. Moreover, the increased superheat degree creates a large temperature difference and enhanced exergy destruction in the heat transfer process of the regenerative system, and the further improvement of thermal efficiency is thus impeded [17,18]. The efficiency could be improved in the steam cycle by utilizing the superheat of extraction steam for heating the feed water from several stages in the turbine. Appropriate superheat utilization of extraction steam by reducing the super degree is an effective approach to further improve the thermal efficiency of double reheat USC power plants. Two measures have been applied to effective utilize the superheat of extraction steam. One adopts an outer steam cooler, which involves setting a surface-type heat exchanger before the regenerative heater (RH) [17]. The superheated extraction steam enters the outer steam cooler, and some of its superheat is used to heat the feed water, which reduces the superheat degree and improves the feed water temperature. Liu et al. [19] investigated the thermal performance of a steam cycle with single reheat after employing an outer steam cooler. Li et al. [20] established a heat circulation calculation model for a thermal system employing an outer steam cooler. These studies have demonstrated that the effectiveness of an outer steam cooler as superheat utilization measure. Using this type of cooler can reduce the superheat degree of extraction steam by more than 100 °C. The other effective means for superheat utilization of extraction steam is to employ a regenerative steam turbine, which was proposed by Kjaer [21,37]. In this scheme, part of the exhaust steam from the high-pressure (HP) turbine flows directly into an extra regenerative steam turbine without entering the reheaters. Several regenerative extraction steam points are set in the regenerative steam turbine to replace those in the intermediate-pressure (IP) turbine. The extraction steam from the regenerative steam turbine is not reheated. Thus, the superheat degree of the extraction steam is significantly reduced by this scheme. This leads to a reduced exergy destruction of the RHs and improves the thermal efficiency of the power plant. Ploumen et al. [23] compared the thermal performance of a common steam/water cycle with the regenerative turbine scheme. The results of the study indicated that the thermal efficiency of the new scheme represented an increase of approximately 0.4 percentage points in a single reheat power plant.

The superheat degree of extraction steam is extremely high because of the two-stage reheat process. Therefore, the reduction in the superheat degree of the extraction steam in double reheat USC power plants is extremely urgent. Moreover, large USC power plants may operate under partial load for peak regulation. Han et al. [24] conducted a simulation study of a lignite-fired power system integrated with flue gas drying and waste heat recovery to present performances under variable power loads. Peng et al. [25] studied the thermodynamic features of a solar aided coal-fired power plant under different load conditions by analysing several operational parameters. The superheat degree of extraction steam increases when the load reduces under the sliding pressure operation mode. Thus, it is necessary to investigate the superheat utilization under partial load operation conditions. Superheat utilization schemes need new equipment and facilities, resulting in an increased power plant investment. Espatolero [26] studied strategies for the efficiency improvement of the feed water heater network designs and provided a techno-economic analysis in SC coal-fired power plants. Rovira et al. [27] investigated thermodynamic optimizations and techno-economic analyses of combined cycle gas turbine power plants, taking into account the frequent off-design operation of the plant. However, few studies have focused on comprehensive thermodynamic and techno-economic comparative analyses of the optimum superheat use of the extraction steam in double reheat USC power plants, especially under low load operation conditions. For this reason, the thermodynamic