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Techno-economic comparison of boiler cold-end exhaust gas heat recovery processes for efficient brown-coal-fired power generation

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ABSTRACT

An important way to increase power plant thermal efficiency is to recover exhaust gas heat at the boiler cold-end with the stepwise integration of a steam turbine heat regenerative system. To this end, there are currently three typical heat recovery processes, i.e., a low-temperature economizer (LTE), segmented air heating (SAH) and bypass flue (BPF), for recovery. To provide useful guidance to thermal power plants for optimal and efficient processes, the thermal economy and techno-economic performance of the three aforementioned processes were calculated and compared using an in-service 600 MW brown-coal-fired supercritical power unit as a reference. The results demonstrate that with the use of these three processes, the net standard coal consumption rate of the unit can be reduced by 4.43, 5.84 and 6.48 g/(kW · h); meanwhile, 3.84, 3.52 and 3.39 million USD are the initial costs of the three heat recovery projects. If the 600 MW unit runs 5500 h per year at the rated load, the three processes can annually increase the earnings of the unit by 1.49, 2.03 and 2.27 million USD from coal savings, meaning that their dynamic payback periods are 3.12, 2.00 and 1.71 years, respectively. The results indicate that for a brown-coal-fired power unit, the coal savings achieved by exhaust heat recovery are significant. In comparison with the conventional LTE, SAH shows an improvement in thermal economy and techno-economic performance, but it currently faces difficulties in engineering applications. Among the three processes, the BPF shows the best thermal economy and techno-economic performance, as well as good engineering feasibility; therefore, it is recommended for application.

1. Introduction

Coal is generally expected to continue to play a key role in the future energy supply because it is the most abundant and cheapest fossil fuel resource. At present, the share of coal in the total primary energy consumption is approximately 30% worldwide, whereas the share in China is approximately 70%. In other words, approximately 50% of global coal consumption is consumed in China. Coal is mostly used as a utility boiler's fuel for power generation. Currently, the share of coal burnt for power generation among the total coal consumption is approximately 63% worldwide, whereas the shares in the USA and China are approximately 91% and 55%, respectively [1]. To a certain degree, a larger share of coal for power generation means cleaner coal utilization, so it is necessary for China to further increase this share for as far as this is possible and allowed within international agreements on CO_2 emissions, such as the December 2015 Paris Agreement.

In 2015, the total electricity consumption in China was 5550 billion kilowatt-hours, from which the electricity from thermal power plants accounted for 73.9%; meanwhile, the average net standard coal consumption rate of thermal power plants is 315 g/(kW · h) [2]. To achieve higher efficiency of thermal power plants and thus reduce the coal consumption rate of power generation, newly constructed power units are often built using a higher live steam parameter such as ultra-supercritical pressure or a more complex steam cycle such as the double reheat system. For the numerous in-service power units, a feasible method for increasing their efficiency must be tapped. For this purpose, several processes called boiler cold-end optimizations, in which the waste exhaust

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gas heat at the boiler cold-end is recovered by the condensate/feed water with a stepwise integration, have been proposed in recent years as an important way to increase the efficiency of thermal power plants.

Of this, the most well-known exhaust gas heat recovery process is the LTE (Low-Temperature Economizer), or low-pressure economizer, which recovers exhaust heat into the heat regenerative system of the steam turbine using the low-temperature condensate as the coolant, thereby elevating the efficiency of the power plant. In Germany, LTE systems were applied to several 900 MW lignite-fired power plants, increasing the plant efficiency by approximately 0.5% as the boiler exhausts were cooled from 170 °C to 130 °C [3]. In China, a LTE system was installed in the Shanghai Waigaoqiao Power Plant with a 1000 MW unit, increasing the plant efficiency by approximately 0.7% as the boiler exhaust was cooled from 125 °C to 85 °C [4]. In addition to the increased plant efficiency, the water consumption of the wet FGD (Flue Gas Desulfurization) system was reduced with boiler exhaust cooling, especially when a gas-gas heater (GGH) was not used because the low temperature exhaust decreased the amount of spray water needed in the cooling tower. According to Wang et al. [5], as a result of using a LTE system, approximately 30 t/h of spray water could be saved by a 600 MW unit with a wet FGD system when the boiler exhaust is cooled from 123 °C to temperatures below 100 °C, while the standard coal consumption rate of this unit is reduced by approximately 3.0 g/(kW.h). To avoid acid corrosion in the ESP (Electrostatic Precipitator), Zhang et al. [6] proposed a two-stage LTE layout, dividing the LTE into two parts and placing them ahead of the ESP and FGD. They tested the performance the LTE layout in a hard-coal-fired 1000 MW unit, with coal savings of 1.6 g/(kW.h) and water savings of 40 t/h. Xu et al. [7] conducted a techno-economic analysis on LTE processes to compare the effect of location selection for an LTE embedded in the condensate flow. They concluded that the techno-economic performance of the flue gas heat recovery in power plants does not always increase with the increment of the recovered heat, but has an optimum recovery point.

To further increase plant efficiency via more efficient flue gas heat utilization after exiting the boiler economizer, some improved processes, including a BPF (Bypass Flue) and SAH (Segmented Air Heating), have recently been proposed and discussed. Owing to the better stepwise utilization of thermal energy for heat-to-work conversion, the thermal economy or coal savings achieved by the BPF and SAH are greater than those of the LTE under the same conditions of quantity of exhaust heat recovered.

According to the literature, the BPF was run in a 1000 MW brown-coal-fired unit in a Niederaussem power plant in Germany in the 1990s, resulting in coal savings of approximately 7.0 g/(kW · h) as the boiler exhaust was cooled from 160 °C to 100 °C [3]. For a hard-coal-fired unit, the coal savings was approximately 3.5 g/(kW · h) because the boiler exhaust was cooled from 130 °C to 90 °C [8,9]. Espatolero et al. [10] conducted a study of a FGB process using a conventional 600 MW unit as the reference and concluded that the power plant efficiency increase was in the range of 0.59%–1.07% as the boiler exhaust temperature was decreased from 125 °C to 90 °C by using FGB systems with different degrees of complexity. In addition, the coal savings was approximately 4.0 g/(kW · h) for a hard-coal-fired unit when the BPF was coupled with a steam air preheater [11]. These results indicated that the coal savings of the BPF were obviously higher than those of the LTE. However, it is still unclear regarding the variations in a BPF in terms of the heating surfaces at the boiler's cold-end, including the added running cost.

In recent years, the concept of setting a LTE forward in the flue gas stream has been proposed, so a higher level of flue gas temperatures and extraction steam savings are obtained for the LTE, thus leading to greater coal savings than by using a conventional LTE. In this conception, the preheating of combustion air is divided into two segments, named SAH herein. According to Xu et al. [12,13], compared with the coal savings of a conventional LTE of 1.23 g/(kW · h), the coal savings of the SAH could be elevated to 2.49 g/(kW · h), wherein the flue gas temperature range of the LTE is elevated from 130–95 °C to 175–140 °C, meanwhile, a LTAH (Low-Temperature Air Heater) is connected to the LTE to cool the flue gas from 140 °C to 95 °C.

Which process is preferable among the abovementioned three processes? The answer is still not clear at present. Although several studies have been conducted comparing the BPF or SAH with the LTE, it is a pity that the previous studies focused only on a comparison of their thermal economy. However, the actual superiority of a heat recovery process should be judged on techno-economic comparisons. Moreover, the previous studies usually used a hard-coal-fired power unit as the research subject, whereas the boiler cold-end optimization of a brown-coal-fired power unit has seldom aroused interest.

Brown coal accounts for approximately 40% of the total coal reserves worldwide. In addition, compared with a hard-coal-fired utility boiler, a brown-coal-fired boiler often shows larger flue gas flow and higher exhaust temperature. Typically, the exhaust temperature and heat loss by exhaust sensible heat for a hard-coal-fired boiler are approximately 125 °C and 5% (of the lower heating value), respectively, whereas those for a brown-coal-fired boiler are approximately 150 °C and 8%. Thus, it is more pressing to implement an exhaust heat recovery process on brown-coal-fired power units.

Therefore, this paper aims to compare the thermal economy and techno-economic performance of the three processes of boiler cold-end optimization—i.e., the LTE, SAH and BPF—by using an in-service 600 MW brown-coal-fired supercritical power unit in China as the reference. The results obtained are expected to provide useful guidance to thermal power plants to choose the optimal process for increased efficiency.

2. Three typical processes of boiler cold-end optimization

2.1. Low-temperature economizer

The LTE, in which an economizer is placed after the RAH (Rotary Air Heater) to cool the boiler exhaust to a temperature of approximately 90 °C by using the condensate as the coolant, has been equipped in many in-service power units through renovation

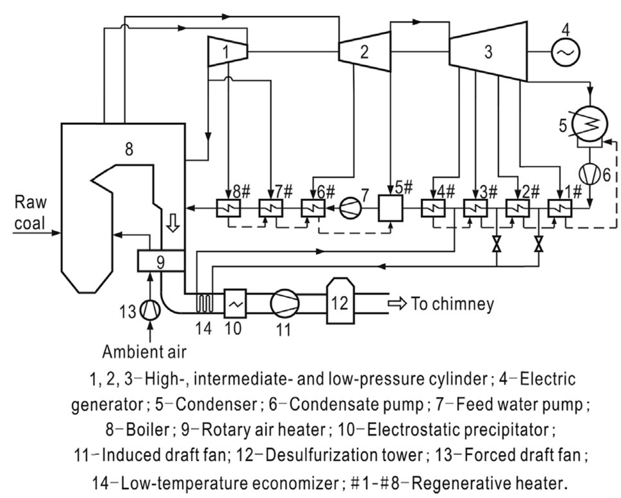

Fig. 1. Schematic of the low-temperature economizer process.