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An environment friendly and efficient lignite-fired power generation process based on a boiler with an open pulverizing system and the recovery of water from mill-exhaust

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ABSTRACT

This paper advances a novel lignite-fired power generation process based on a OPSB (boiler with an open pulverizing system) and the recovery of water from mill-exhaust after the comprehensive analysis of the open pulverizing system used for high-moisture coals and heat/water recovery from boiler exhaust. Then, the thermal calculation method that applies to OPSB is presented based on heat and mass balance analyses of the boiler. Finally, an efficient unit applying the OPSB process is compared with a conventional 600 MW lignite-fired power unit, and the performance of the efficient unit is calculated and discussed in detail. The results show that the efficient unit not only yields a notable increase in the boiler's (2.6%) and the power plant's (1.3%) thermal efficiency but also provides a remarkable advantage in water recovery due to the mass of water vapor concentrated in mill-exhaust. In the efficient unit, the volume fraction of water vapor in mill-exhaust reaches 34%, the water reclaimed from mill-exhaust is so much that a lignite-fired power plant with zero water consumption can be expected, while the pollutant emissions can be reduced in proportion to the increase in boiler thermal efficiency.

1. Introduction

Lignite accounts for approximately 40% of total coal reserves worldwide. In China, lignite accounts for approximately 13% of coal reserves and is predominantly distributed in the northern regions of the country [1]. Lignite generally features low energy, high water content (25–65%) and high amounts of volatiles and is capable of spontaneous combustion. Because of these features, most lignite is not suitable for long-distance transportation. To increase the efficient utilization of lignite in addition to its sales radius, a variety of lignite drying technologies have been advanced and researched in recent years. Among these methods, steam-drying technology, which uses the waste heat of low-pressure steam extracted from the turbine in thermal power plants to pre-dry lignite, has been widely considered and analyzed by means of process simulations. Kakaras et al. [2] performed a computer simulation on plant thermal efficiency with three types of steam-heated lignite dryers—a rotary drum dryer, a fluidized bed dryer and a mechanical thermal dewatering process—and concluded that the improvement in overall plant efficiency varied between 3% and 5%, depending on the water content of the raw coal and on the degree of pre-drying. Liu et al. [3] compared a thermodynamic analysis of a lignite-fired power plant with the flue gas pre-drying and the steam pre-drying methods and concluded that the steam pre-drying method could improve plant thermal efficiency more than the flue gas pre-drying method. However, heat transfer between the coal particles and the steam in existing steam-heated dryers is indirect, yielding low heat transfer efficiency; hence, these steam-heated dryers must be quite large, resulting in significant equipment investment and substantial operating costs.

Flue gas drying technology applies a direct mixing of flue gases and coal particles by means of a fluidized bed, a moving bed, a pneumatic conveyor tube or other means. Wang [4] conducted an experimental investigation on the drying process of three types of Illinois coals with a laboratory fluidized bed using air as the drying agent. Hao [5] tested lignite drying with a 200 t/h pilot downstream drying pipe using high temperature flue gas as the drying agent. Tian [6] performed an experimental study on lignite drying in a straight upstream pipe using air as the drying agent, as well as the conveying medium. Theoretically, flue gas drying has higher heat transfer efficiencies than dryers with a surface type heat transfer. However, flue gas drying also suffers serious challenges related to operating safety.

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Care must be taken to avoid spontaneous combustion; to this end, strict control of air leakages and the drying gas' oxygen content must be maintained, which is presently difficult to achieve.

Non-evaporative drying technologies, such as hot water drying and mechanical thermal expression systems, have exhibited advantages like low energy consumption during drying and the removal of some alkali metals from coal, which are conducive to mitigating the slagging and fouling of boilers, as ascertained by Favas and Jackson [7] and Bergins [8]. However, this approach is limited by the high temperature and high-pressure conditions associated with dewatering, with the result being that dewatering equipment is difficult to upsize to full production scales. Additionally, the wastewater discharged from dewatering systems is unsuitable for most reuse scenarios due to its acidic, salty and carbon rich nature, as indicated by Butler et al. [9]. Clearly, the various lignite drying technologies each have their own difficulties, and before any of these technologies can be applied to large-scale engineering operations, they must be further researched and improved. Other common challenges with the independent lignite drying process include dried lignite's inherent spontaneous combustibility, which makes it difficult to store and transport, and its frangibility, which makes it difficult to form into briquettes.

At present, most lignite is to fire a boiler to generate electricity at pithead power plants. In a sense, the coal pulverizing system of power boilers is also a mature drying system. Several sets of lignite-fired power units in the 600 MW class have been put into operation in China, and all were assembled with direct-fired pulverizing systems. However, compared with more common bituminous-coal-fired boilers, the thermal efficiencies of lignite-fired boilers are approximately 2% lower, and the price of lignite-fired boilers is approximately 25% higher. These are mainly a result of the increased flue gas flow in lignite-fired boilers and the direct-fired pulverizing system. Typically, the flue gas flow in the furnace and tail flue of a lignite-fired boiler is approximately 50% and 30% greater than that of a bituminous-coal-fired boiler, with the result being that the lignite-fired boilers often yield higher flue gas heat losses and larger boiler volumes. On the other hand, because thermal power plants often consume substantial water to maintain their operations, the conflict between power development and local environmental sustainability has become increasingly pronounced. In China, for instance, most lignite-producing regions are short on water resources, and this water scarcity seriously restricts the local construction of a power base as well as local economic development. Therefore, this paper advances an environmentally friendly, efficient, lignite-fired power generation process based on a OPSB (boiler with an open pulverizing system) and on the recovery of water from the pulverizing system's exhaust (hereafter called mill-exhaust).

2. Principles of the efficient lignite-fired power generation process

2.1. Analysis of the pulverizing systems used for high-moisture coals

As a result of the needs for safety and reduced power consumption of pulverizing systems, large-scale lignite-fired boilers are often assembled with fan mills or medium-speed mills. Medium-speed mills usually use hot air as a drying agent. Due to the limited drying capacity of hot air, medium-speed mills are often applied to lignite with relatively low moisture content. In cases where the total moisture content in raw coal is greater than 30%, the use of a fan milling system—using a three-component gas (hot flue gas, hot air and cold flue gas) or a two-component gas (hot flue gas and hot air) as the drying agent—is recommended to achieve sufficient drying capacity. In comparison with an indirect-fired pulverizing system, a direct-fired pulverizing system has several advantages, including a compact layout, lower equipment investment and power consumption, and enhanced operating safety. Hence, almost all fan mills and medium-speed mills are working in the direct-fired pulverizing systems at present.

However, for a boiler fired with high moisture coal, it is necessary to extract high temperature flue gas from the boiler as the major drying agent; in this case, the application of a direct-fired pulverizing system makes the primary air to boiler contain a mass of inert flue gases and water vapor. These inert gases in the primary air not only hurt the stable ignition of pulverized-coal but also increase the flue gas flow in the boiler, resulting in increased flue gas sensible heat loss from the boiler. For a boiler fired with young lignite, which usually carries a moisture content greater than 40%, the stable ignition of pulverized-coal cannot be ensured because there is too much inert gas in the primary air; in this case, an available countermeasure is the placement of pulverized-coal concentrators before the burners. At the same time, pulverized-coal concentrators augment powder-feeding resistance, decreasing mill output, which sometimes causes a reduction in the power unit's output.

Even in an indirect-fired pulverizing system, in which the mill-exhaust (usually called the third air) enters the boiler at the top of the furnace to burn out the fine coal contained in mill-exhaust, the mass of low-temperature mill-exhaust gives an impact on the furnace temperature, thus the heat loss by unburned carbon is apt to increase. It can be observed that with a closed pulverizing system, the mill-exhaust with a mass of inert gases entering the furnace always reduces the stable and efficient combustion of pulverized-coal and tends to increase the flue gas sensible heat loss. Therefore, an open pulverizing system would benefit both pulverized-coal combustion and boiler thermal efficiency for high moisture coal-fired boilers.

Investigators in the former Soviet Union and Germany had tried to develop open pulverizing systems for lignite in the 1960s through 1980s [10]. However, due to the low separation efficiency of pulverized-coal collectors, which at that time were multi-tube cyclones or electrical precipitators, the heat loss by the flying coal in mill-exhaust amounted to approximately 2.5% [10]. Coupled with the environmental pollution caused by flying coal emission, open pulverizing systems were gradually phased out of use for lignite-fired power generation. However, along with the technical progress on pulverized-coal collectors—especially bag filters—the use of open pulverizing systems is now viable for thermal power plants. This opinion is drawn from references on similar open pulverizing processes used for blast furnaces in the steel industry, and from the pulverized-coal preparation process in the cement industry, where bag-filters play the role of terminal pulverized-coal collectors, and exhibit reliable separation performance with exhaust dust content lower than 30 mg/Nm^3. Moreover, the use of open pulverizing systems has not been atypical in Chinese thermal power plants, such as the Jiangyou (2 $\times$ 330 MW) and Yahekou (2 $\times$ 350 MW) thermal power plants. In these power plants, the boilers are equipped with open pulverizing systems with ball mills and pulverized-coal bunkers to ensure the ignition, stable combustion and complete burnout of tinpot meager coal and anthracite. The separation efficiencies achieved for their bag-filters were higher than 99.90%, and their open pulverizing systems are currently running in good condition [11]. Hence, the application of open pulverizing systems to lignite-fired units is entirely feasible at present. Nevertheless, in pulverized-coal collectors, the issues associated with their explosiveness must be solved properly before use.

2.2. Analysis of the recovery of heat and water from the exhaust of coal-fired boilers

The recovery of heat from the exhaust of power boilers has received significant attention in recent years. A popular approach is