Research Progress of Flexible Peak Shaving Technology for Coal-Fired Boilers

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Abstract. In the face of the pressing challenges of climate change and carbon emissions, China's energy and power sectors are actively working towards the strategic goal of establishing a new power system, where wind and solar energy will constitute a rapidly expanding portion of grid-connected power generation. Nevertheless, the inherent characteristics of these renewable energy sources, such as their randomness, intermittency, and volatility, pose significant challenges to ensuring the secure and stable operation of the power grid. Presently, China heavily relies on pulverized coal power plants, which lack the flexibility required to accommodate the fluctuating demands posed by renewable energy generation. Overcoming this technical obstacle and enabling efficient grid integration of renewable energy necessitates a thorough exploration of the potential of existing pulverized coal furnaces for flexible peaking operations, especially under extreme peak shaving conditions. To address this challenge, coal self-preheating combustion technology has emerged as a pioneering solution developed by the Institute of Engineering Thermophysics, Chinese Academy of Sciences. By implementing preheating modification activation, this innovative approach alters the traditional combustion reaction path of pulverized coal, significantly enhancing its reaction activity. This advancement holds immense promise for achieving efficient and stable combustion, as well as facilitating rapid load changes in pulverized coal boilers operating at low loads. This study primarily focuses on discussing prevalent means of peaking technology, including low-load stable combustion technology, rapid load regulation technology, coupled peaking technology, and the development status of peaking technology for coal power units. Through in-depth research and innovation, it is anticipated that the effectiveness and viability of peaking technology will be further enhanced, promoting the sustainable development of pulverized coal boiler generating units and optimizing the operation of energy systems. Furthermore, the self-preheating combustion technology will increasingly play a pivotal role in multiple sectors and directions, such as flexible and deep peaking of coal power, driving the advancement and adoption of clean and effective coal utilization technology.

Keywords: Pulverized coal boiler, Peak shaving, Self-preheating combustion, Low-load stable combustion, Rapid load change.

1. Introduction

The achievement of China's "double carbon" target necessitates several measures, including improving energy efficiency, controlling total fossil energy consumption, implementing renewable energy alternatives, and constructing a clean, low-carbon, secure, and efficient energy system [1]. In recent years, there has been a rapid expansion in wind and solar power generation capacity and installed capacity [2]. By 2022, wind and solar power generation capacity is projected to account for 14.3% and 15.5% of the total installed capacity, respectively. However, the intermittent, random, and volatile nature of these energy sources leads to significant wind and solar abandonment during grid-connected power generation [1, 3], presenting substantial challenges to the operation of a secure and stable power grid. Flexible peaking on the power side is crucial for minimizing grid fluctuations and utilizing renewable energy effectively. Oil-fired, gas-fired, and pumped-storage power facilities serve as valuable contributors to the power system peaking [4]. Oil-fired power plants can respond rapidly to peak demands, providing stable and reliable power output, but they come with high fuel costs and require regular maintenance and replacement, which increases the operating expenses of the power system [5, 6]. Additionally, the operation of oil-fired power facilities generates large quantities of polluting exhaust gases and effluents. Gas-fired power plants offer high combustion efficiency and low pollutant emissions, making them an excellent source of peaking power [7]. However, China's current proven natural gas reserves are relatively small [8], and the high production costs of gas-fired units limit their large-scale deployment. Pumped storage power plants offer numerous advantages, including peak regulation, frequency regulation, and black-start emergency backup functions [9]. However, their installed capacity needs improvement to effectively balance power supply and demand, owing to limitations related to water resource distribution, geological conditions, and investment costs [10]. Presently, China's installed capacity of flexible regulating power sources must be expanded to meet the growing peaking demand resulting from the increasing fluctuations in the power grid [11]. Therefore, it is imperative to explore new sources of peaking power.

China's vast coal-based energy resources make coal-fired power generation the primary source of power supply in the country. In the new energy landscape, pulverized coal power plant furnaces are expected to play an increasingly important role in peaking operations, thanks to their significant peaking potential and operational flexibility [3, 12]. However, the current participation of coal-fired power plant boilers in grid peaking through low-load operation poses several challenges that must be addressed to ensure safe and efficient coal-fired boiler operation [13]. Operating coal-fired boilers at low loads can lead to difficulties in coal ignition, reduced combustion stability, and even boiler flameout, posing substantial safety risks [14]. Prolonged low-load operation also negatively impacts various systems, including the combustion process, boiler performance, and auxiliary systems, resulting in increased pollutant emission concentrations, decreased combustion efficiency, and increased equipment degradation [15]. Furthermore, the presence of thermal inertia in boiler systems hinders rapid load response [16]. Compared to gas-fired units, coal-fired units have slower load response times, making it challenging to effectively respond to load fluctuations caused by the integration of renewable energy sources and maintain a balance between power supply and demand in the grid [17]. Moreover, abrupt or frequent load variations can lead to system instability, component fatigue, creep, and a shortened unit lifespan [18]. In general, utilizing coal-fired units to contribute to the power system's flexible peaking still faces the challenges of achieving stable combustion at low loads and improving response rates for variable loads. Overcoming these challenges is essential to ensure the safe and efficient operation of coal-fired power plants while supporting the power system's flexible peaking requirements.

The Institute of Engineering Thermophysics, Chinese Academy of Sciences (IET, CAS) has developed the coal self-preheating combustion technology that could effectively address the challenges faced by conventional coal-fired units in flexible power peaking [19]. This innovative technology operates on the principle of feeding pulverized coal into a self-preheating burner, where it undergoes partial combustion and gasification reactions, transforming into a thermally active fuel consisting of a gas/solid two-phase mixture with a temperature exceeding 800°C [20, 21]. During the preheating process, several beneficial changes occur to the pulverized coal. The particle size becomes finer, the pore structure improves, the graphitization degree decreases, and the number of active defect sites increases [22, 23]. These modifications significantly enhance the reactivity of the fuel, activating and optimizing its combustion characteristics. The combustion process of the gas/solid thermally active fuel is dominated by a homogeneous reaction, akin to the combustion of gaseous fuels, thereby shifting away from the conventional heterogeneous reaction path of pulverized coal combustion [21, 24, 25]. This transformation addresses issues such as flameout and poor combustion efficiency that are typically encountered when operating pulverized coal boilers at low loads. Consequently, stable and efficient combustion at low loads is achieved, ensuring the reliable and efficient operation of the boiler [22, 26, 27]. Furthermore, under rapid variable-load conditions, the combustion reaction rate of the gas-phase components in high-temperature preheated fuel is significantly higher compared to conventional cold pulverized coal combustion. This elevated reaction rate enables the preheated fuel to respond to variable loads more rapidly, providing increased flexibility in meeting fluctuating power demands [19, 21].

To alleviate the present peaking pressure, consume a high proportion of new energy power, and advance China's transition to a low-carbon energy system, fully exploiting the high peaking potential and rapid load-changing capability of pulverized coal power plant boilers is paramount. To provide a reference for the future development of deep and flexible peaking technology for pulverized coal boiler generating units, it is necessary to organize and summarize the extant peaking technology of pulverized coal power plant boilers in China. This study introduces the problems of stable combustion at low load and rapid load response encountered in the peaking operation of pulverized coal power station boilers, as well as the corresponding technical advancements. It proposes the novel concept of applying the preheated combustion technology of pulverized coal to the peaking operation of power station boilers. The research can provide theoretical guidance for peaking pulverized coal boilers and encourage peaking technology's advancement and industrial application.

2. Stable combustion technology of pulverized coal under low load

Operating a unit at a low load can result in a decrease in the average temperature of the boiler chamber. This temperature reduction can give rise to various issues, including challenges with coal powder ignition, compromised combustion stability, and significant safety hazards such as fire extinguishing and furnace chamber explosions. To address these concerns, several technical solutions have been experimentally validated to enable sustained combustion at low loads in pulverized coal furnaces. This study primarily concentrates on key areas such as boiler combustion reformation, burner reformation, and fine adjustments. These areas have been identified as crucial for achieving improved performance and stability at low loads. Through innovative approaches and modifications in these aspects, the aim is to enhance the combustion process, optimize burner functionality, and fine-tune operational parameters to overcome the challenges associated with low-load operation in pulverized coal furnaces.

2.1. Combustion retrofit

Modifying the combustion makes it possible to increase the stability of the boiler's low-load operation when the unit is profoundly peak shaving. Among the various combustion methods available, two commonly employed techniques are plasma ignition technology and micro oil ignition technology.

2.1.1 Plasma ignition

Plasma ignition technology operates by utilizing direct current to generate an arc in the plasma carrier air, resulting in a stabilized DC air plasma. This plasma creates a high-temperature zone within the central combustion cylinder of the burner. As pulverized coal particles pass through this zone, they rapidly release volatile fractions, causing the coal particles to break down and undergo rapid combustion. Plasma ignition technology offers several advantages over traditional fuel ignition methods, including enhanced safety, reduced fuel consumption, and lower operating costs for power plants. As a result, it has become increasingly prevalent [28]. Zhang et al. [29] developed a novel lignite plasma burner characterized by its simple structure, low resistance, excellent anti-coking performance, and strong ignition capabilities. They achieved successful oil-free plasma ignition in a 300 MW lignite unit boiler with a high total moisture content of 35% to 40% in the raw coal fed into the furnace. During ignition, the new high-moisture lignite burner operated stably, with a continuous bright flame at the nozzle, demonstrating its strong adaptability to various working conditions. Zhao et al. [30] conducted a study on the plasma-assisted ignition mechanism and its effects on the ignition and combustion of pulverized coal. They validated the performance of plasma ignition by constructing a non-premixed combustion chamber. The results demonstrated that plasma ignition technology effectively reduced the ignition delay time of pulverized coal while significantly enhancing the ignition capacity. Furthermore, Messerle et al. [31] conducted numerical studies on plasma combustion systems and observed that plasma-assisted combustion resulted in a 16% reduction in the concentration of unburned carbon at the furnace outlet compared to conventional coal combustion. This improvement in combustion efficiency also led to a 34% reduction in NO_x emissions, thereby enhancing the overall combustion characteristics of the furnace.

2.1.2 Micro oil ignition technology

Micro-oil ignition technology involves the atomization of fuel oil into ultra-micro oil droplets using compressed air. The high-temperature burning of these oil droplets ignites the concentrated stream of pulverized coal gas within the central cylinder of the thick and light burner, followed by the introduction of secondary and tertiary air-pulverized mixtures. Li et al. [32] employed a micro-oil ignition scheme, enabling a 330 MW boiler to achieve ignition in a cold furnace while ensuring the complete combustion of pulverized coal. This approach resulted in a reduction in oil consumption of over 95% while meeting the requirements for stable boiler combustion during ultra-low load operations below 30%. Liu et al. [33] conducted reaction flow experiments on a full-scale experimental apparatus to analyze the effects of varying oil flow rates. Their research aimed to understand the impact of oil feed rate on the ignition of lean coal. In a separate study, Li et al. [34] performed full-scale reaction flow experiments and proposed the use of a "little oil ignition burner" to minimize oil usage during ignition and low-load operation. These studies highlight the effectiveness of micro-oil ignition technology in achieving reliable ignition and combustion of pulverized coal.

Both plasma ignition and micro-oil ignition technologies have made significant advancements in improving the stability of boilers during low-load operation. However, there are notable differences in terms of coal type adaptability, system reliability, and economics. Plasma ignition technology is well-suited for volatile coal types, such as bituminous coal and lignite, while the arc generation process in plasma ignition technology can be unstable, and the system structure is often complex, resulting in lower reliability. Additionally, implementing plasma ignition technology requires a substantial investment in equipment. On the other hand, micro-oil ignition technology exhibits adaptability to various coal types, including poor-quality bituminous coal, lignite, poor coal, and anthracite. This technology is highly reliable and requires relatively low investment in equipment. Considering the coal type adaptability, system reliability and economy, micro-oil ignition technology is better than plasma ignition technology and is a favorable choice to improve the stability of boiler low load operation.

2.2. Burner Selection and Retrofit

In the pursuit of enhancing stable combustion capacity in pulverized coal boilers, selecting suitable burners plays a crucial role. Numerous studies have been conducted to analyze the applicability of different burners, providing valuable insights for selecting burners for low-load operations. Notably, burner modifications during peak shaving have yielded promising results. According to Meng et al. [35], boilers equipped with DC burners can benefit from the use of double-channel self-stabilizing burners to achieve stable combustion at lower loads. Boilers equipped with swirling burners, on the other hand, can utilize dense radial fade and HT-NR burners, among other options. Furthermore, experimental studies focusing on swirling burner selection have introduced innovative ideas for burner modifications in various pulverized coal furnaces, yielding positive outcomes [36, 37]. A notable example is the work of Kang et al. [38], who replaced the original burner of an ultra-supercritical pulverized coal boiler with a horizontal thick and light burner. Following this modification, the combustion stability of the boiler improved significantly, and both the central steam temperature and reheat steam temperature showed noticeable enhancements. The modified boiler was capable of achieving stable combustion at a 40% rated load. Song et al. [39] discussed the primary factors limiting the significant improvement of low-load steady combustion performance in swirling burners. They proposed that enhancing the efficient concentration of pulverized coal and high-temperature flue gas reflux, as well as optimizing the burner's operational parameters, could lead to the development of swirling burners with robust and stable combustion capabilities.

In addition to the previously discussed modifications involving DC and swirling burners, new types of burners have been introduced [40, 41]. Tan et al. [42] introduced a novel low-temperature, low-nitrogen, double nitrogen vortex preheating solution burner, in which pulverized coal is first preheated at a high temperature and then mixed and ignited with the high-temperature flue gas of the coal suction. The burner tests demonstrated stable flame combustion at 30%-35% of the burner's design power, with a boiler efficiency reaching 92.75%. Moreover, when installed in the middle or upper front and rear walls of swirling or DC combustion systems, the new burner enables steady combustion at 10%-20% low load. Shen et al. [43] proposed a new form of induction heating technology that utilizes coal-fired fuel in a DC burner, allowing for the ignition of coal particulates within 80s. By advancing the high-temperature flame area near the DC burner by approximately 1.6m, a broad range of heat load regulation, from 13.6% to 100%, can be achieved. Another new swirl burner (NSB) is proposed by Wang et al. [44]. Experimental studies demonstrated that the use of NSB-improved boilers significantly enhanced stable combustion at ultra-low loads. The minimum load for stable combustion in 300 MW boilers without oil support was reduced from 150 MW to 90 MW, while maintaining ultra-low NO_x emissions performance. These new burner technologies offer promising solutions for achieving stable combustion at low loads. They demonstrate improved combustion efficiency, reduced emissions, and expanded operational ranges, contributing to the overall performance optimization of boilers.

2.3. Refinement adjustment

Fine adjustment primarily involves modifying the pulverizing system, coal blending, auxiliary equipment, and other measures to achieve stable combustion at a low unit load. This process focuses on optimizing various aspects of the system to ensure efficient and reliable operation even under low load conditions.

2.3.1 Modification of powder-making system

When operating under low-load conditions, the adaptability of the pulverizing system is a critical factor in ensuring stable combustion. To enhance the performance of the pulverizing system during deep peaking operation, it is essential to strengthen its management and optimize its functionality. This can be achieved by increasing the coal mill output, installing additional peaking coal pulverizing systems, and implementing coal pulverizing concentration technology [3]. Hong et al. [45] conducted optimization and adjustments to the pulverizing system of a 660 MW supercritical boiler, resulting in improved low-load stabilization combustion capability. This modification ensured stable peak operation at up to 30% of the rated load, while also enhancing the boiler's efficiency and NOx control performance. Ma et al. [46] proposed a modification to increase the granularity and concentration of pulverized coal in the small pulverizer bin, enabling stable combustion at low loads.

Furthermore, retrofitting coal mill dynamic separators has emerged as a well-established strategy. Zhang et al. [47] have found that modifying the coal mill dynamic separator to reduce the fineness of coal powder while increasing its uniformity index effectively enhances the low-load stabilization combustion capacity of the boiler. Wang et al. [48] optimized the operation mode of the coal mill dynamic separator using a 660 MW ultra-supercritical unit in Shaanxi as a case study. By adjusting the dynamic separator frequency to 38 Hz, they achieved a decrease in pulverized coal fineness at the mill outlet, a downward shift of the combustion flame center, a significant increase in pulverized coal burnout rate, and a noticeable decrease in the carbon content of the ash. As a result, the boiler achieved stable combustion at 22.7% of the rated load in the unassisted combustion mode.

Reducing the output of the coal mill has proven to be an effective solution to address vibration issues. Yong et al. [49] conducted a study on the feasibility of reducing coal mill output in a low-load coal-fired unit. They found that under low-load conditions, when high-calorific-value coal is used and the coal quantity in each coal mill is low, commissioning three coal mills can lead to more stable boiler combustion, reduced impact of load fluctuations on boiler parameters, and decreased power consumption of the pulverizing system. However, when low-volatile coal is burned, it is still necessary to commission four coal mills. In another development, Yang et al. [50] introduced a resonant peaking pulverizing system that, when combined with an intermediate storage bin type pulverizing system, improves boiler combustion stability at a low load of 30%. This approach reduces the number of coal mills in operation, avoids combustion instability caused by reducing coal mill output, and allows real-time adjustment of the fuel quantity required for boiler combustion, thereby enhancing the unit's load response rate.

2.3.2 Coal blending

The coal blending scheme plays a crucial role in achieving stable combustion and optimal performance, especially when dealing with low-volatile coal. By implementing effective coal blending management practices, ensuring incoming coal quality, and stockpiling high-quality coal, the combustion stability and deep peaking performance of boilers can be significantly improved. Ran et al. [51] conducted an in-depth analysis of the economic and safety aspects of incorporating off-design coal in a 660 MW coal-fired unit, taking into account the adaptability of boiler equipment. Reasonable coal integration resulted in enhanced combustion stability, improved denitrification performance, and reduced combustion costs for the unit. Huang et al. [52] studied a 330 MW subcritical unit and achieved safe and stable operation under severe peaking conditions ranging from 25% to 45% by blending 80% quasi-east coal with the incoming coal mass, while maintaining a minimum boiler thermal efficiency of 93.1%. Qi et al. [53] investigated the ignition behavior and combustion performance of pulverized pyrolysis coal mixed with powdered bituminous coal at various mass fractions. Qiao et al. [54] examined the co-combustion of semi-coking coal (SC) and bituminous coal (BC) in an oxygen-enriched atmosphere. Their findings indicated that higher oxygen concentrations lowered the ignition and combustion temperatures of the SC-BC mixture compared to lower oxygen concentrations. Moreover, at a 30% oxygen concentration, the synergistic effect between SC and BC was enhanced, resulting in improved combustion efficiency. These studies highlight the significance of coal blending in optimizing combustion performance and achieving efficient and stable operation of coal-fired units.

2.3.3 Auxiliary equipment renovation

During low-load peaking operations, the adaptability of auxiliary equipment is crucial for ensuring the safe and efficient operation of the unit. Long-term low-load operation of coal-fired units can lead to issues such as coal mill vibration and fan instability [1, 3]. One approach to improve fan stability is the implementation of single-sided fan operation. Wu et al. [55] conducted a single-side fan operation test on a subcritical 330 MW unit during the low load stage. The results demonstrated that single-side fan operation maintained the unit's regular operation at 30% of the rated load, resulting in electricity savings of 0.37%-0.73% and a reduction of coal consumption by 13g/kWh, leading to significant economic benefits. In addition, Li et al. [56] proposed a novel modification scheme for the booster fan of a 350 MW-rated unit, focusing on a low-speed drive fan. This modification scheme was successfully implemented, improving the stability of the unit under 175 MW low-load conditions and 95 MW peaking severe conditions. The fan's operating efficiency and regulation accuracy were enhanced, resulting in annual cost savings of approximately 381,000 RMB. These studies highlight the importance of auxiliary equipment adaptability in addressing issues related to low-load peaking operation, leading to improved stability, energy savings, and cost reduction for coal-fired units.

2.4. Comparison of pulverized coal low load stabilization combustion technologies

Various solutions for low-load stabilization combustion offer different levels of system complexity, operating costs, and technical advantages and disadvantages. Combustion retrofit has the advantage of practical stabilization effects but comes with the drawback of system complexity, high operating costs, and the potential need for equipment upgrades. Burner retrofit, on the other hand, offers lower operating costs but may be less effective in achieving direct blast system reform. Retrofitting the pulverizing system and auxiliary equipment provides a relatively simple solution that effectively addresses issues such as coal mill vibration and fan wheezing. However, pulverizing system modifications may result in poor load response performance. Coal blending is another approach that can enhance combustion efficiency by combining high-volatile matter quality coal with low-quality coal, but it often comes at a higher cost. In the operation of coal power plants, it is crucial to carefully weigh the pros and cons of different retrofitting options and make flexible modifications based on specific circumstances.

3. Research progress of fast variable load peaking technology of pulverized coal combustion

During unit peak regulation, the load response rate plays a crucial role as it indicates how quickly the unit can adjust its load in response to changes in power demand from the grid. The dynamic nature of power demand requires rapid load response from the unit. Therefore, it is vital to carefully explore effective solutions that can enhance the unit's ability to handle load fluctuations and develop improved strategies based on these findings. Many commonly used technical methods focus on the steam side of the system and include techniques such as condensate throttling, vapor extraction regulation, and feedwater bypass throttling. By implementing these techniques, the unit can better respond to changes in power demand and maintain stable and reliable operation during peak regulation.

3.1. Condensate throttling

The condensate variable load control technique is a turbine-side storage regulation method that involves adjusting the condensate flow to achieve rapid load changes in the unit. By decreasing the pumping flow of the low-pressure heater and increasing the steam flow entering the low-pressure cylinder, the unit can respond quickly to load variations [57]. Wang et al. [58] developed a condensate throttling model and an enhanced coordinated control strategy (CCS) by integrating conventional coordinated control with condensate throttling. Their experiment on a 17 MW coal-fired power plant demonstrated that condensate throttling maximized the load variation requirements, and the CCS was able to trace the load command within a sufficient regulation period. They also applied condensate throttling to a 1000 MW power plant and designed a dual controller to achieve combined control of fuel flow and condensate flow, thereby increasing the rate of load variation and restoring the condensate flow and water level in the deaerator [59]. Zhang et al. [60] conducted a study on the relationship between enhanced flexibility and thermal efficiency of coal-fired generating units during condensate throttling. By selecting an appropriate condensate regulation strategy, they were able to reduce cycle losses by up to 51.46%, providing valuable insights for improving the operational flexibility and thermal efficiency of thermal power plants using condensate throttling. Dong et al. [61] investigated the impact of condensate throttling on a 1000 MW unit load study and found that it could achieve a maximum regulation power of 54.679 MW (100% THA) and 31.642 MW (40% THA), with a sufficient regulation period for the CCS to follow the load command effectively.

Condensate variable load regulation technology is a crucial method for improving the rapid load response of power units. It is widely utilized in turbine-side energy storage systems and is considered the most mature technology in this field. However, this regulation technology does have certain limitations. One of the challenges is the lag in load response, which means it may take some time for the unit to adjust to changing load conditions. Additionally, frequent fluctuations in the deaerator water level can occur, posing operational challenges. This scheme only works in the early stages of load changes and has limited regulation capacity, which still needs further research.

3.2. Vapor extraction regulation technology

Vapor extraction regulation is a technique that utilizes the heat storage within the thermal system to rapidly increase the steam quantity working in the medium and high-pressure cylinders. This is achieved by adjusting the opening of the high-pressure heater regulating valve without compromising the unit's safe and stable operation or the quality of heat supply. Among the various vapor extraction regulation techniques, high plus extraction and heating extraction regulation have been extensively researched. Zhao et al. [62] developed a dynamic simulation model for a coal-fired power plant to investigate the operation of a 660 MW supercritical coal-fired unit with high plus vapor extraction regulation. The results demonstrated that the unit's maximum variable load rate could reach 6.1%

(40.89 MW/min) after applying vapor extraction regulation. Furthermore, high-pressure pumping throttling can effectively address issues related to reheating steam over temperature. For example, Wang et al. [63] proposed an optimization method of a gas throttling-assisted coordinated control strategy, which led to a significant reduction in the variation of reheat steam temperature and an increase in the maximum variable load rate from 1.5 %/min to 4.5 %/min. This improvement greatly enhanced the peaking flexibility of power plants.

3.3. Feedwater bypass regulation technology

The feedwater bypass regulation technology operates on a principle similar to condensate variable load technology. It involves rapidly adjusting the feedwater flow through the high-pressure heater, which instantly increases the steam quantity available for the high- and medium-pressure cylinders to perform work, enabling rapid load variation. This solution can quickly restore the high-plus water supply, minimizing the impact on the unit's safety and profitability. However, implementing feedwater bypass adjustment requires more complex modifications to the original feedwater system. Compared to low-pressure heater extraction steam, high-pressure heater extraction steam has a greater work capacity for the same quality of work. This results in a higher capacity to regulate unit load and greater operational flexibility when utilizing this technology. When considering economy, safety, and operational flexibility, the potential for regulating pumped steam from low-pressure heaters surpasses that of high-pressure heaters. Additionally, the potential for modulating circulated steam in steam piping exceeds that of feedwater/condensate bypass measures in terms of load change rate [64]. Wang et al. [65] proposed a load regulation method based on feedwater bypass throttling and pumping throttling. Simulation results indicate that this scheme can effectively respond to medium and high-frequency load commands under varying loads, offering advantages over conventional feedwater heater pumping throttling regulation schemes. Liu et al. [66] proposed a scheme to enhance the efficiency of thermal power plants by modifying the speed of axial air-cooled fans. They also combined the cold-end regulation method with condensate suppression, leading to significant improvements in the load adjustment range and adjustment time. In the operation of thermal power plants, it is essential to consider the advantages and disadvantages of the aforementioned methods to select the most suitable rapid variable load regulation method. Furthermore, it is prudent to consider the synergistic operation of multiple variable load schemes.

4. Coal self-preheating combustion technology

Coal self-preheating combustion technology is an innovative approach to achieve clean and efficient combustion of pulverized coal. It has been developed by the Institute of Engineering Thermophysics, Chinese Academy of Sciences, and finds applications in various industrial boilers, power station boilers, hot air furnaces, and kilns. This technology offers several advantages, including excellent adaptability to solid fuels, low NO_x emissions and flexible load regulation capabilities. Leveraging these unique characteristics, the self-preheating combustion technology shows promising potential for achieving stable combustion and rapid load response, especially at low loads.

4.1. Basic principles of self-preheating and preheated fuel combustion

In the combustion process of gas/solid thermally active fuels, the dominance of the homogeneous phase is analogous to the combustion of gaseous fuels [21, 26]. This shift in combustion mechanism from heterogeneous reactions dominant in conventional solid pulverized coal combustion to homogeneous reactions predominant in gas/solid thermally active fuel combustion is made possible through the preheating modification. As a result, the reaction activity and combustion rate of pulverized coal are significantly enhanced, addressing the limitations of other peaking solutions.

The existing combustion technologies often suffer from drawbacks such as high operating costs, complex installation and commissioning processes, and high levels of NO_x emissions. Additionally, the coal powder used in these technologies is typically "cold coal powder." In contrast, the preheating combustion process utilizes primarily "hot gas" and "hot coal powder" as input reactants. This results in a more uniform distribution of combustion temperature throughout the entire combustion area, eliminating the presence of localized high-temperature zones. Furthermore, the maximal temperature difference between the combustion chamber and the chamber of a conventional pulverized coal furnace is significantly reduced. When combined with temperature and flame characteristics, the preheated fuel could achieve flameless combustion, ensuring uniform heat transfer within the combustion space and leading to lower NO_x emissions [23, 24, 67]. The use of an oxygen-rich atmosphere (O_2/CO_2) is particularly advantageous for achieving flameless combustion with preheated fuel compared to an air atmosphere (O_2/N_2) [68]. The overall combustion rate within the combustion chamber depends on the combustion rate of the preheated coke, as the combustion rate of high-temperature gas is instantaneous and rapid. In contrast, the combustion reaction of the preheated char occurs gradually. In the diffusion combustion control mode, the combustion rate of the preheated coal in the combustion chamber is primarily influenced by the oxygen diffusion rate. To enhance combustion efficiency, several factors are beneficial, including a smaller particulate size distribution [23], higher preheating temperature [69], higher primary air equivalent ratio [70], lower secondary air equivalent ratio [71], and higher oxygen concentration [72].

4.2. Laboratory Study on coal self-preheating combustion technology

Lyu and Niu [22] firstly investigated a novel process that involves preheating pulverized coal to 800 °C before it is fed into the combustion chamber for complete combustion. It was verified that the circulating fluidized bed combustion process, operating at a low air-fuel ratio, can consistently deliver high-temperature preheated fuel with excellent combustion stability and high efficiency. Subsequently, Wang et al. [72] conducted experiments on preheating combustion using anthracite. The results demonstrated that preheated fuel derived from anthracite exhibited good stability and temperature distribution uniformity in the combustion chamber. As long as the total excess air ratio and preheating temperature are within reasonable ranges, variations in operating parameters had minimal impact on the combustion characteristics of anthracite. Building upon these findings, Ouyang et al. [73] further explored the application of coal self-preheating combustion technology in the anthracite and semi-coke combustion. The studies analyzed the characteristics of anthracite preheating conversion, combustion, NO_x formation, and desulfurization. The results revealed that the coal self-preheating combustion technology could achieve efficient, stable, and clean combustion of low-volatile fuel. For further utilization of low volatile fuels, Zhou et al. [74] conducted a study on the structure of the self-preheating burner and the flow characteristics of fine powder fuel with cold experiments. The results indicated that the circulating ratio of the self-preheating burner without an air distributor structure was the highest. Additionally, the agglomeration and sedimentation of gasification residual char had an impact on the efficiency of the cyclone separator.

In addition to investigating combustion adaptability, researchers have also focused on exploring methods to reduce NO_x emissions with coal self-preheating combustion technology. Zhu and He [75] conducted combustion experiments on semi-coke on a 0.2 MW pilot-scale test rig, achieving the lowest NO_x emission value of 178 mg/Nm^3 (@6%O_2), and further explored the influence of air distribution mode on NO_x emissions. The results demonstrated that increasing the air equivalent ratio of the self-preheating burner and adjusting the tertiary air distributions backward along the combustion chamber could effectively reduce NO_x emissions. Yao et al. [76] investigated the impact of air distribution mode on NO_x emission characteristics of Datong bituminous coal and fine semi-coke using coal self-preheating combustion technology. The results revealed that increasing the preheating temperature and the primary air equivalent ratio contributed to NO_x reduction. The primary air equivalent ratio had a more significant effect, facilitating the early removal of fuel nitrogen during the preheating process. Liu [77] conducted an in-depth analysis of the operational characteristics of the self-preheating burner, flameless combustion characteristics and the formation characteristics of NO_x on a 30 kW bench-scale test rig. The findings indicated that most of the volatile matter was released during the preheating process, primarily transforming into N_2 and a small amount of NH_3.

Reasonable organization of air distribution and enhanced fuel-air mixing in the reduction zone effectively inhibited NO_x formation. Subsequently, Zhang et al. [69] achieved an original NO_x emission level of 50 mg/Nm^3 (@6%O_2) for Shenmu bituminous coal by increasing the primary air equivalent ratio and the preheating temperature, while Liu et al. [26] employed a low primary air equivalent ratio of 0.21-0.22 on a 2 MW pilot-scale text rig, achieving an original NO_x emission level of 49 mg/Nm^3 for Shenmu bituminous coal, maintaining a combustion efficiency of 98.7%.

4.3. Industrial application of coal self-preheating combustion technology

Based on coal self-preheating combustion technology, the Institute of Engineering Thermophysics, Chinese Academy of Sciences has successfully designed and developed a range of self-preheating burners with capacities ranging from 14 MW to 64 MW. These burners are specifically designed for use in boilers that employ pulverized coal, semi-coke, and gasification residual carbon self-preheating combustion. In the case of pulverized coal self-preheating combustion industrial boilers, two types of boilers are covered: pulverized coal self-preheating burner bottom-fired boilers and self-preheating burner side-fired boilers. The self-preheating burner bottom-fired boiler has a capacity grade of 40t/h [78]. The preheated fuel is injected upward from the bottom of the furnace, while the secondary air is evenly distributed around the preheated fuel nozzle at the furnace's bottom. The burnout air is divided into two layers. The secondary air equivalent ratio can be adjusted flexibly between 0.2 and 0.6, and the total air equivalent ratio in the main combustion zone can be as low as 0.4, ensuring effective ignition and stable combustion. Operational results demonstrate that when bituminous coal is used as the fuel, the combustion temperature remains below 1100℃, and the boiler achieves a thermal efficiency higher than 92%. The original emission of NO_x is lower than 100 mg/Nm^3. On the other hand, the self-preheating burner side-fired boiler has a capacity grade of 60t/h. In this boiler, the preheated fuel is injected horizontally on both sides of the furnace, while the secondary air flows perpendicular to the horizontal injection direction of the fuel. The burnout air is divided into upper and lower layers. Operational results reveal that when bituminous coal is used as the fuel, the combustion temperature remains below 1250℃, and the boiler achieves a thermal efficiency higher than 90%. The original emission of NO_x is lower than 150mg/Nm^3. Moreover, this boiler exhibits a wide load regulation range of 10% to 100% (6t/h~60t/h). Furthermore, two 90t/h pulverized coal self-preheating combustion boilers are already operational. Additionally, a 35t/h pulverized coal self-preheating combustion boiler specifically designed for semi-coke with low volatile content has been developed [79]. The operational results demonstrate that this boiler can seamlessly switch between Shenmu bituminous coal and semi-coke (volatile content ranging from 8% to 30%). The combustion temperature remains below 1200℃, and the semi-coke combustion efficiency exceeds 99%. The original NO_x emission reaches a minimum of 116mg/Nm^3. In addressing the residual char produced by circulating fluidized bed coal gasification (volatile content is 1.6%), a 100t/d gasification residual char self-preheating combustion boiler [80] has been developed. The operational results indicate that when the combustion temperature remains below 1100℃, the combustion efficiency exceeds 98%, and the original emission of NO_x is lower than 200mg/Nm^3.

Currently, the Institute of Engineering Thermophysics, Chinese Academy of Sciences is actively conducting a demonstration of flexible peak shaving for the self-preheating combustion of pulverized coal-fired power plant boilers. This demonstration encompasses both traditional coal-fired electric boilers and supercritical CO_2 coal-fired electric boilers. By transforming a single solid fuel into a high-temperature gas-solid mixed fuel, the self-preheating burner enhances the performance of pulverized coal self-preheating combustion technology, particularly in ultra-low load scenarios. Presently, stable operation at load levels ranging from 10% to 20% has been successfully achieved using a 60t/h pulverized coal self-preheating combustion boiler. In situations with rapidly varying load demands, the combustion reaction rate of gaseous components in the high-temperature preheated fuel is increased. This leads to improved load variability compared to conventional cold pulverized coal combustion. Furthermore, the application of coal self-preheating combustion technology is poised to expand into various fields, such as solid waste management and iron and steel smelting.

5. Conclusion and Prospect

In order to achieve the objective of "double carbon" and promote the development of a sustainable power system, the construction of coal-fired generating units with deep peak shaving capabilities is crucial. Given that coal-fired power sources play a significant role in the power system, it is essential to conduct thorough research on the deep peaking capability and variable load rate of coal-fired furnace generating units. China has developed mature peak shaving technologies, primarily focusing on low load stabilization combustion and rapid load variation. These technical solutions offer distinct advantages in terms of peaking participation and other aspects. However, their practical application still requires further improvement. By implementing coal self-preheating combustion technology in peaking pulverized coal boilers, it is expected that profound peaking at low loads and rapid response to variable loads can be achieved. Therefore, enhancing the deep-peaking capability of these units can be effectively accomplished by considering the following factors:

(1) In order to tackle the issue of insufficient low-load stable combustion performance in pulverized coal power plant boilers, it is crucial to prioritize the renovation of the combustion side of the boiler. This renovation should aim to achieve optimal performance under severe peaking conditions, taking into account considerations of safety, reliability, and economics. A key aspect of this renovation process is to focus on the selection and transformation of furnace burners. Comprehensive research should be conducted to identify suitable burner options and develop fine-tuning techniques. It is essential to strike a balance between achieving optimal combustion performance and considering the economic aspects of the transformation.

(2) To improve the load change rate of coal-fired units, several effective methods can be employed, including condensate throttling, steam flow regulation, and feedwater bypass regulation. These technologies allow for the adjustment of the working mass flow rate through high and low-pressure radiators, enabling rapid load changes. In industrial applications, the coordinated operation of multiple variable load technologies is crucial. Therefore, it is necessary to thoroughly examine the scheme for rapid variable load on the combustion side of the boiler. This involves investigating and exploring more effective concepts and strategies for achieving variable load capabilities.

(3) The application prospects for coal self-preheating combustion technology in achieving flexible peaking of pulverized coal burners are highly promising. Self-preheating combustion transforms the conventional solid fuel combustion into a gas-solid mixed combustion, offering significant benefits such as stable combustion at low loads and rapid response to variable boiler loads. One of the notable advantages of coal self-preheating combustion technology is its role in pollutant emission control, particularly in reducing NO_x emissions. By utilizing coal self-preheating combustion, the future of research will focus on exploring the peaking potential of this technology. This includes realizing the pure and efficient utilization of coal and enabling the flexible peaking of pulverized coal boilers.

(4) Future pulverized coal boiler generating units will be oriented toward more intelligent and adaptive flexible peaking technology, focusing on essential indicators such as coal combustion efficiency, pollutant emission reduction, and taking deep and flexible peak shaving of coal-fired units as the next technological innovation direction to achieve the deep integration and clean utilization of both traditional energy sources and renewable energy.

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