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Improving the Flexibility of Coal-Fired Power Plants via a Pre-Gasification Burner with Ultra-Enhanced Flame Stability

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ABSTRACT

To maintain power grid stability under the increasing integration of renewable energy, the operational flexibility of thermal power plants is assuming growing significance. Flame stability and responsiveness on the combustion side under the extreme conditions of ultra-low loads and rapid load-change processes are the key to increasing the flexibility of thermal power plants. In this paper, a burner based on pre-gasification combustion technology is developed. The flexibility of the pre-gasification burner on a 5-MW pilot platform is investigated through simulation and performance verification. The results indicate that a single pre-gasification burner can maintain flame stability under a 9% load when burning bituminous coal, and a fuel load variation rate of 10% min^{-1} can be supported. The pre-gasification combustion has a faster stabilization rate compared with traditional combustion under coal flow and air flow disturbances. The application of pre-gasification burners in different classes of boiler is simulated, and the results indicate that the pre-gasification burner has the potential to improve the flexibility of industrial to full-scale coal-fired boilers.

1. Introduction

Renewable energy is expected to form the main part of the energy structure in future. By 2030, China plans to reach a combined wind and solar power capacity of 1.2 billion kW·h to fulfil its objectives of reaching a carbon peak and carbon neutrality [1]. However, the strong volatility and intermittency of renewable energy generation pose a huge challenge to the stability of the power grid [2]. As the main component of China's power generation structure, thermal power must be used as a regulating power supply to compensate for fluctuating renewable energy generation [3]. Therefore, it is necessary to improve the flexibility of thermal power plants [4].

For improved flexibility, thermal power plants must be able to operate under a wide load range [5] and rapidly changing loads [6]. Flame stability is the key to improving the flexibility of the combustion side of coal-fired boilers. Common methods to improve flame stability include raising the primary air temperature, reducing the fineness of pulverized coal, and optimizing the air distribution [7]. The core concept of these methods is to reduce ignition difficulty by adjusting the operating scheme [8]. At present, some of China's thermal power plants can operate under a 30% load. Li et al. [9] achieved stable operation under a 30% load on a 330-MW boiler by means of micro-oil ignition. Ang [10] improved the combustion process of a 350-MW supercritical boiler operating under a 30% load by adjusting the upper burner and lowering the primary air rate. Nonetheless, different boilers differ significantly in their structure and the type of coal used, and determining a safe and appropriate operating scheme takes a long time and has a high cost.

Many studies have improved boilers' capacity to deal with load changing by adding an energy-storage link. Trojan et al. [11] proposed a scheme to improve the flexibility of thermal power plants by installing a hot water storage tank to achieve a power ramp rate of up to 7.32% min^{-1}. Dong [12] proposed a multi-storage cooperative scheduling system for a thermal power plant and applied it to a 600-MW boiler. Their results showed that a load-changing rate of 29.4 MW·min^{-1} could be achieved. The above studies indicate that,

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through control strategies and the addition of energy storage, it is possible to enhance the peak shaving capacity within the current operating range of thermal power plants. However, adding an energy-storage link requires a large investment and increases the complexity of the thermodynamic system. In fact, the key to further expanding the operating range of thermal power plants lies in the flame stability of the combustion side [13]. To increase flexibility, the combustion technology must be upgraded to enable the combustion side to support flexible operation.

In recent years, the pulverized coal preheating method has been demonstrated to have great potential to enhance flame stability [14]. This technology has been developed through various stages. The concept was first developed by the All-Russian Thermal Engineering Institute [15,16], which developed gas fire coal preheating (GFCP) and realized coal preheating by means of flue gases from burning natural gas. Wang et al. [17] and Zhu et al. [18] proposed a coal preheating method using a circulating fluidized bed (CFB) and conducted experiments that showed that the coal preheating method with a CFB can realize the clean combustion of inferior fuels such as anthracite coal [19] and semi-coke [20]. Lyu et al. [21] further delved into the concept of preheating combustion and proposed a pre-gasification combustion route. Instead of just being preheated or pyrolyzed, the pulverized coal is first modified via gasification to obtain high-temperature gasification products. The excess air coefficient of the gasification process was further optimized by Ruan et al. [22,23] for the control of nitrogen oxides (NO_x) and particulate matter (PM). Pre-gasification combustion technology has significant advantages for flame stability and NO_x control, and its application can increase the flexibility of thermal power plants.

In this paper, a pre-gasification burner aimed to improve the flexibility of coal-fired thermal power plants is developed. A detailed study is carried out, ranging from laboratory experiments to industrial-scale applications and full-scale boiler simulations. The improvement of pulverized coal combustion via pre-gasification is investigated through a constructed experimental apparatus. The flexibility of the pre-gasification burner is studied using computational fluid dynamics (CFD) and Aspen Dynamics simulations, respectively. Based on the simulation findings, a 5-MW coal-fired boiler is used to test the pre-gasification burner, and the minimum stabilized combustion load and the capability for rapid fuel load changing are explored. The application of pre-gasification burners in larger coal-fired boilers is also investigated through simulations. The results of these efforts reveal the potential of the pre-gasification burner to increase the flexibility of coal-fired thermal power plants from the combustion side.

2. Research method

2.1. Experimental setup

To study the effect of pre-gasification modification on the combustion of pulverized coal, a 75-kW pulverized coal gasification combustion test rig was designed and constructed in the laboratory. The rig included two parts: a pre-gasifier and a combustion furnace. The pulverized coal first reacts with part of the air in the gasifier; it then enters the combustion furnace to realize combustion. A site picture of the rig is shown in Fig. 1(a), and details of the structure are provided in Ref. [24]. Sampling ports are arranged along the pre-gasifier and combustion furnace for extracting the flue gas and determining the distribution of gas components in the rig. The gasification products—both gases and solids—can be collected during the experiment through the sampling port at the outlet of the pre-gasifier. The effect of pre-gasification modification on pulverized coal combustion can then be explored by analyzing the gasification products.

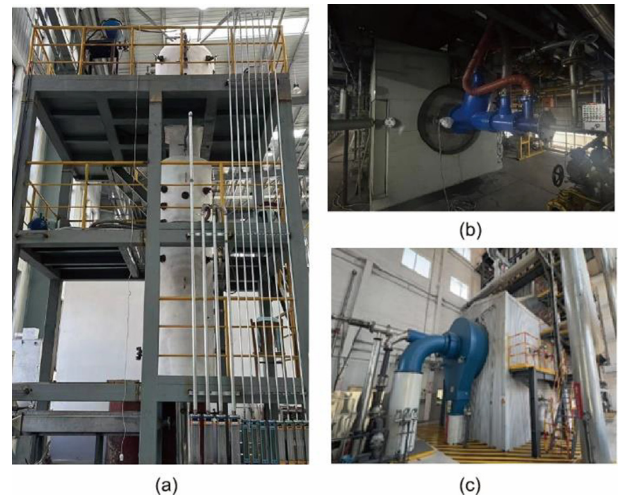

Fig. 1. The experimental setups in this study: (a) the 75-kW laboratory rig; (b) the 5-MW pilot platform; (c) the 29-MW industrial boiler.

After the design of the pre-gasification burner was completed, based on the design concept, different burners were sized, machined, and implemented to match the power of a 5-MW pilot platform and a 29-MW industrial boiler, respectively, as shown in Figs. 1(b) and (c). A full flexibility test of the pre-gasification burner was conducted on the 5-MW pilot platform. The sectional dimensions (internal cross-section) of the pilot platform are 2 m × 2 m, with a total length of 6 m. To facilitate temperature measurement, the pre-gasification chamber is equipped with movable B-type thermocouples. The horizontal furnace is equipped with a number of viewing holes, which can be used to measure the temperature along the length of the furnace by means of an infrared temperature-measuring gun. The deep peaking capability of the pre-gasification burner was also tested on a 29-MW industrial boiler. Table 1 provides details on the fuel properties.

2.2. Numerical model implementation

In this study, three different classes of coal-fired boilers fitted with pre-gasification burners were simulated using CFD methods. A schematic diagram of the pre-gasification burner and the construction of the three boilers is shown in Fig. 2. The pre-gasification burner mainly consists of a pre-gasification chamber, along with the primary air, internal secondary air, and external secondary air flows. The pre-gasification chamber is the core of the burner. Highly concentrated pulverized coal reacts with the primary air and internal secondary air in the chamber. A compartment was designed between the primary air and the internal secondary air to regulate their mixing. The first backflow zone forms in the pre-gasification chamber. The gasification products then mix with the external secondary air for a combustion reaction after entering the furnace. The outlet of the pre-gasification chamber is encircled by the external secondary air, which forms a second backflow zone in the furnace.

The modeling of the turbulent flow, heat transfer, and chemical reactions of the pulverized coal combustion was performed using ANSYS Fluent 2019 R2. The velocity and pressure fields were solved by means of the SIMPLE algorithm. Given the swirl flow in the simulation, the realizable k–ε model was adopted as the turbulence model [25,26]. As it was worth considering the mutual radiation between the pulverized coal, the discrete ordinates (DO)

Table 1
Coal properties in this study.

Fuel	Situation	Proximate analysis (wt%; ad)				Ultimate analysis (wt%; daf)					Q_{net} (MJ·kg^{-1}; ar)
		V	FC	A	M	C	H	O	N	S	
Bituminous coal	Laboratory rig	33.54	54.37	7.44	4.65	80.18	4.90	13.51	0.94	0.47	27.19
	5-MW platform	31.03	48.34	14.02	6.61	80.66	4.97	12.70	1.14	0.53	24.32
	29-MW boiler	31.16	51.14	12.53	5.17	75.27	5.24	17.16	1.18	1.15	25.27

V: volatile; FC: fixed carbon; A: ash; M: moisture; Q_{net}: net calorific value; ad: air-dried; daf: dry ash-free; ar: as received.

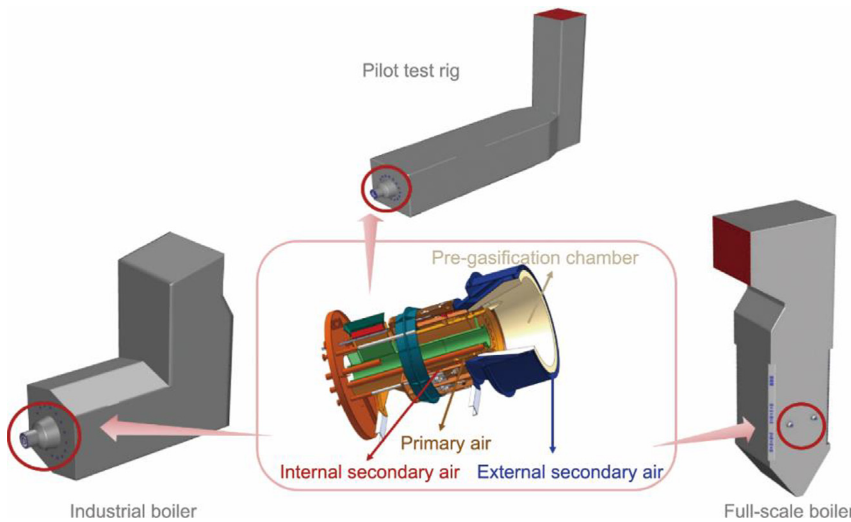

Fig. 2. Geometric modeling of the pre-gasification burner and boilers.

model was utilized to simulate the radiative heat transfer [27]. The weighted sum of gray gases model (WSGGM) [28,29] was used to calculate the radiation absorption coefficient of the gas phase. To predict the devolatilization process of the pulverized coal, the two-competing rates model was utilized, since this model has been widely substantiated in investigations of the thermal–chemical process of solid fuels [30]. For the combustion of volatiles, the volatile matter in coal can be regarded as a single component, with its composition assumed to be $C_aH_bO_c$ according to element conservation [31]. The kinetic/diffusion-limited model was used to simulate the combustion of char [32]. Verification of the grid independence and specific boundary condition settings for all models is provided in Refs. [33–35]. After the grid independence check, a grid of 950 000 was used for the 5-MW pilot platform model, and a grid of 1 180 000 was used for the 29-MW boiler model. The calculations were considered to have converged when the residuals of the energy equation and the heat transfer equation were less than 10^{-6} and the residuals of each of the other terms were less than 10^{-4}. In addition, the O_2 concentration in the outlet cross-section and the average temperatures and velocities in the center cross-section of the furnace had to be stabilized.

2.3. Aspen Dynamics model implementation

The pre-gasification combustion process was modeled using Aspen Plus, and the steady-state model was transformed into a dynamic model by means of flow driving. Fig. 3 depicts the flowsheet diagram. The whole combustion process was divided into three stages: rapid decomposition, the gasification reaction, and the combustion of gasification products.

Because of coal's complex components, it must first be decomposed into a simple substance to make it possible to define the subsequent reactions. This decomposition process can be simulated using the RYIELD module (DECOMP), integrated with the FORTRAN subroutines to calculate the yield of each substance [36]. In the next step, the decomposed substance reacts with part of the air in the pre-gasification chamber to yield the gasification products. The RGIBBS module (GASI) was chosen to simulate the reaction process at this stage, considering the phase and chemical equilibrium [37]. The conservation of energy should be satisfied between the two processes; that is, the heat required for the decomposition of the pulverized coal should be provided by the pre-gasification reaction heat. Finally, to model the combustion process of the gasification products in the furnace, the RSTOIC module (G-BURN and C-BURN) was adopted [38]. The main reactions assumed to occur in the combustion process are shown in Table 2. Considering the rapidity of the homogeneous reactions compared with the heterogeneous ones, the sequence of reactions in the reactor is specified. It is assumed that the combustion of hydrogen gas (H_2), methane (CH_4), and sulfur (S) occurs rapidly, followed by the char combustion reaction [39].

3. Results and discussion

3.1. Improving combustion via the pre-gasification reaction

To evaluate the effect of pre-gasification on pulverized coal combustion, experiments were carried out using a 75-kW pulverized-coal gasification combustion test rig [40]. The gas components along the rig were analyzed, and the results are shown in Fig. 4 [40]. In the pre-gasifier, the concentrations of CO and H_2 decreased significantly at 300 mm—that is, at the location of the burner arrangement, where O_2 entered and rapidly consumed the CO and H_2. In the other areas of the gasifier, due to the low O_2 concentration, CO and H_2 were produced by the gasification reaction of pulverized coal. The concentration of CH_4 remained relatively

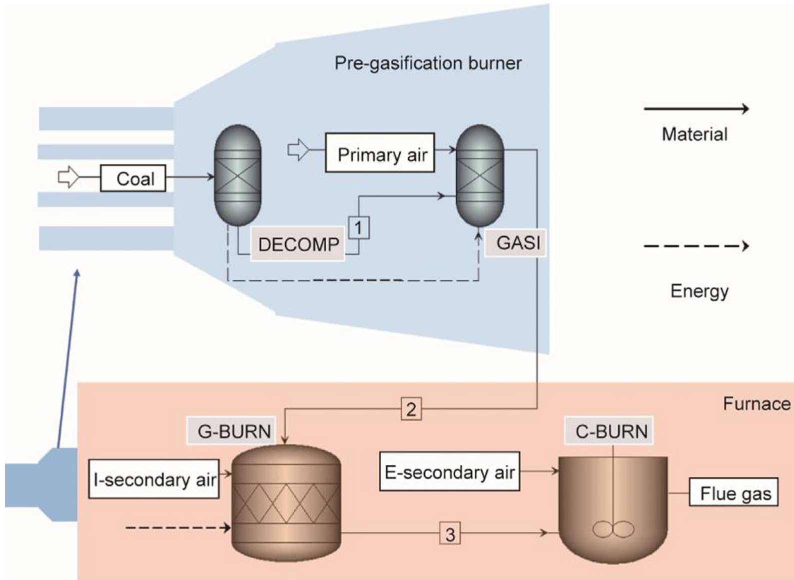

Fig. 3. Simulation flow diagram of the pre-gasification combustion system. DECOMP: the RYIELD module; GASI: the RGIBBS module; G-BURN and C-BURN: the RSTOIC module; I: internal; E: external.

Table 2
Reactions specified in the RSTOIC module.

No.	Reaction	Reactant
1	$H_2 + 0.5O_2 \rightarrow H_2O$	H_2
2	$CH_4 + 1.5O_2 \rightarrow 2H_2O + CO$	CH_4
3	$S + O_2 \rightarrow SO_2$	S
4	$C + 0.5O_2 \rightarrow CO$	C
5	$CO + 0.5O_2 \rightarrow CO_2$	CO

Table 3
Aspen simulation results and experimental results.

Item	Concentration (%)			
	CO	H_2	CO_2	CH_4
Simulation result	12.5	8.2	10.2	0.89
Experiment result	13.2	8.7	11.2	0.95

constant in the gasifier due to the low reaction rate. After pre-gasification, about 54% of the gasification product was gasified gas, and the rest was gasified char. The gas components at the gasifier outlet were analyzed. As shown in Fig. 4, the concentrations of CO and H_2 were 13.15% and 8.72%, respectively, which can promote ignition and stable combustion of the gasification products. After entering the combustion chamber, each combustible gas was rapidly consumed, reflecting a good combustion intensity.

For subsequent research using the Aspen model, the accuracy of its simulation was verified after obtaining experimental data. Table 3 demonstrates the errors between the gasification products predicted by the Aspen model and the experimental values, all of which are within 10%.

The combustion kinetics of raw coal and gasified char were analyzed using a thermogravimetric analyzer with a heating rate of 20 °C·min^{-1} and a final temperature of 1000 °C. The test results are shown in Fig. 5(a) [40], including the thermogravimetry (TG) and derivative thermogravimetry (DTG) curves of raw coal and gasified char. The ignition temperature of the raw coal was 439 °C, and

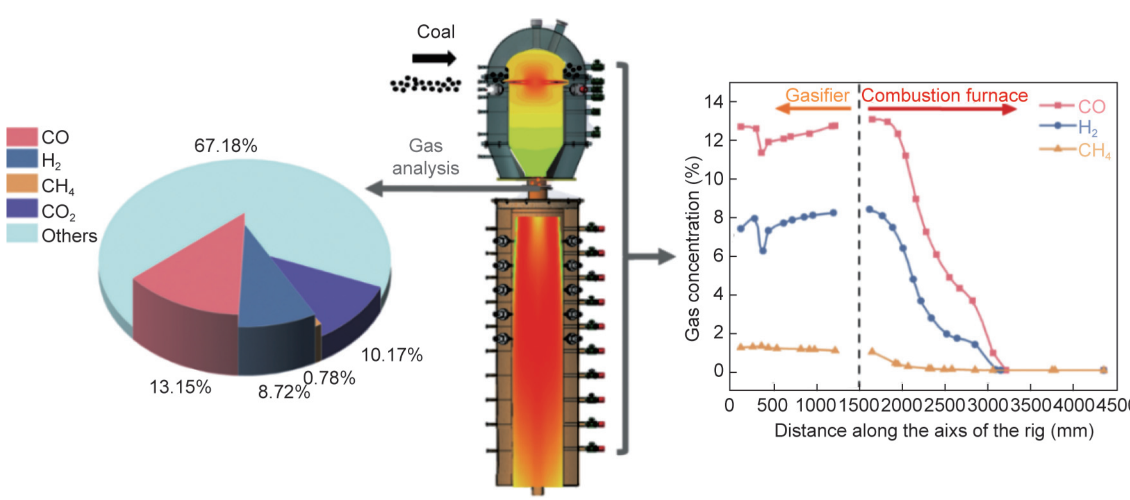

Fig. 4. Gas distribution along the central axis in the 75-kW gasification combustion test rig.

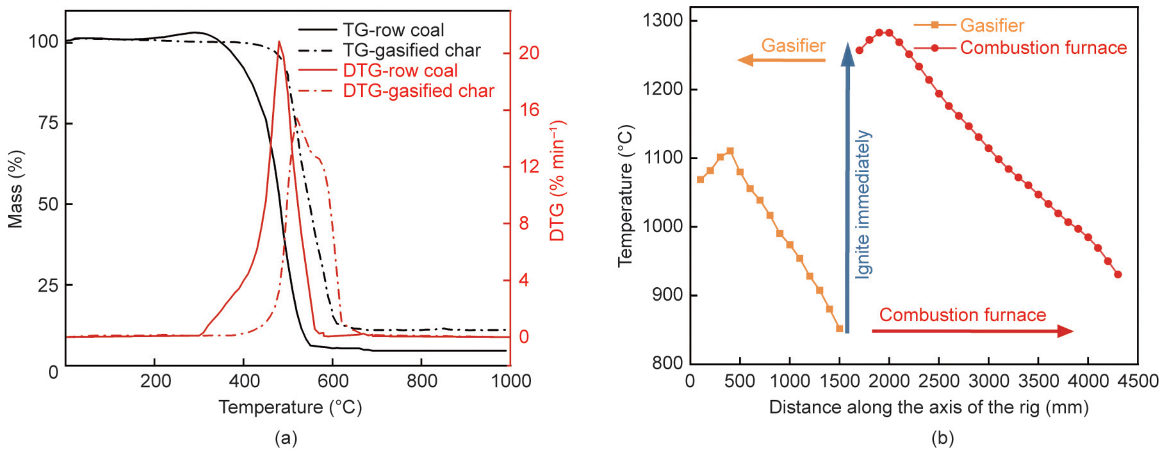

Fig. 5. (a) Thermogravimetric analysis of raw coal and gasified char; (b) temperature distribution along the central axis.

the ignition temperature of the gasified char increased to 492 °C. This increase in ignition temperature can be explained by the release of most of the volatiles in the gasification process. Although the ignition temperature increased slightly, the exit temperature of the gasifier was 850 °C, as shown in Fig. 5(b). This is because part of the pulverized coal already underwent gasification and combustion in the gasifier, and the gasifier operated self-sustainably even under a low load to ensure stable combustion. Therefore, the gasified char was immediately ignited upon entering the combustion chamber. All these results indicate that pre-gasification creates easier combustion conditions and can increase flame stability.

3.2. Application of the pre-gasification burner on a 5-MW pilot platform: Simulation and experiments

3.2.1. Numerical simulation under an ultra-low load

The flame stability of the pre-gasification burner under an ultra-low load was first studied by means of numerical simulations and was compared with that of a traditional burner without a pre-gasification chamber. To exclude the possibility of computational errors, a traditional burner without a pre-gasification chamber was first validated under high loads [41], demonstrating that the computational model accurately represented the physical phenomena in the furnace. The boundary conditions of the two models—such as the fuel input, outlet pressure, and wall temperature—were kept consistent, so that only the burner structures differed. Fig. 6 shows a comparison of the temperature distribution in the horizontal furnace of the two burners under a 10% load. Removing the pre-gasification chamber makes it difficult for the traditional burner to maintain combustion under a 10% load. During the iterative calculations, the furnace rapidly lost temperature, causing a non-convergent result. In contrast, the pre-gasification burner still achieved ultra-enhanced flame stability under a 10% load.

It is considered that the reaction within the pre-gasification chamber is critical in maintaining flame stability. The optimization of the air distribution for the pre-gasification burner under an ultra-low load was investigated previously by our research group, as reported in Ref. [33]. Fig. 7 shows the gas content along the axial direction of the 5-MW platform equipped with a pre-gasification burner under a 10% load. By optimizing the air distribution, flue gas reflux is formed in the pre-gasification chamber, which is conducive to the reaction of high-concentration pulverized coal, thus ensuring the release of heat. As shown in Fig. 7, some of the pulverized coal is consumed inside the pre-gasification chamber, resulting in a rapid decrease in the O_2 concentration in the pre-gasification chamber. Since the excess air coefficient in the pre-gasification chamber is less than 1, the CO concentration increases. The O_2 concentration rises when the gasified mixture is combined with the external secondary air after it enters the furnace. The O_2 is then rapidly consumed, heating the mixture and causing it to combust in a reducing atmosphere.

3.2.2. Pre-gasification burner experiment on a 5-MW pilot platform

Combustion experiments on a single pre-gasification burner were completed on a 5-MW pilot platform to investigate the minimum steady combustion load and rapid combustion load-change capability [42]. The load was gradually reduced from 100% while monitoring the temperature, flame stability, and composition of the exit flue gas. As the load decreased, the temperature at the outlet of the furnace gradually decreased, while the temperature in the pre-gasification chamber remained stable. A weakening of the flame stability was observed as the load continued to drop from 9%. The load was then restored to 9%, and the boiler continued to run for 1 h. The outlet oxygen content, pre-gasification chamber temperature, and furnace outlet temperature during the operation period are shown in Fig. 8 [42]. After the first 10 min of fluctuation, the outlet oxygen content remains stable, while the outlet temperature of the furnace continues to decline. This is because the reaction under an ultra-low load is concentrated in the front zone of the furnace, and the flame becomes shorter. The decreasing trend slows down after 40 min, and a temperature of 700 °C is still maintained after 1 h. Notably, the temperature in the pre-gasification chamber remains stable throughout the 9% load operation, and a reaction is achieved at 750 °C. This is the core of the stabilized flame. The results show that the minimum steady combustion load of the pre-gasification burner is up to 9%, which is consistent with the numerical simulation result.

Next, a rapid combustion load-changing experiment for a range in loads from 15% to 100% was conducted. For the 5-MW pilot platform, since there was no heating surface, the load could only be judged based on the fuel input. Therefore, the load-changing rate given herein is for the fuel input load. First, a rapid load-reduction experiment was carried out. After stabilizing at a full load, loads of 75%, 50%, and 30% were used as stage values; after stabilizing at each stage, the load reduction was continued down to a load of 15%. To ensure ideal combustion at each stage, the air distribution for different loads was determined in advance through steady-state experiments. Fig. 9(a) [42] shows the monitoring curves of the key parameters during the rapid load-reduction process. The load-reduction process took 8 min, and the calculated load-changing rate was 10.6% min^{-1}. As the load decreases, the outlet temperature of the furnace continues to decrease. The outlet oxygen generally shows a pattern of a slow increase as the load decreases.

Similarly, a rapid load-rise experiment for a range in loads from 15% to 100% was conducted; the parameter monitoring curves of this process are shown in Fig. 9(b). The load-rise experiment took 9 min, and the calculated load-changing rate was 9.4% min^{-1}. The time required to increase the load was longer than that required to reduce the load within the same regulation range. The experiment results show that the pre-gasification burner supports a rapid fuel load change of 10% min^{-1}.

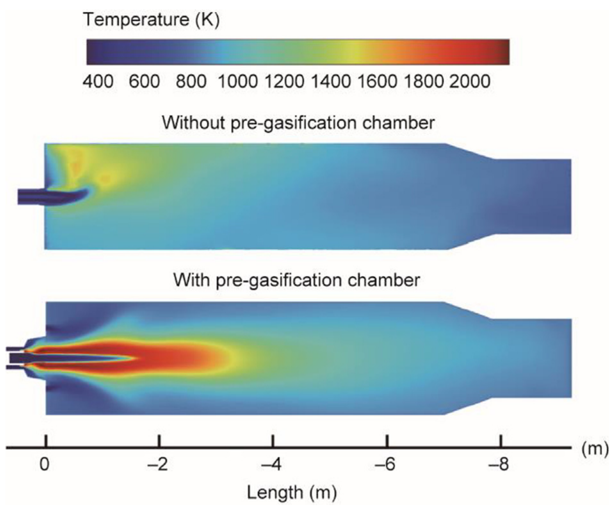

Fig. 6. Temperature fields in the horizontal furnace of two burners under a 10% load.

3.2.3. A typical step signal disturbance analysis

Based on the developed Aspen Dynamics model, the dynamic response characteristics of pre-gasification combustion on a 5-MW platform were studied. A traditional combustion model was also built for comparison. In contrast to the pre-gasification combustion model shown in Fig. 3, the traditional combustion model lacked the pre-gasification module and consisted only of pyrolysis and combustion modules, since it did not have a pre-gasification phase. The total step disturbance of the superposition of both the coal flow and the air flow is discussed below.

First, the dynamic characteristics of the flue gas temperatures of pre-gasification combustion and traditional combustion were compared for a stepwise change in the combustion load from a 100% load to a 75% load. As shown in Fig. 10(a), after 5 s of stable operation, an overall step disturbance occurs (including a coal flow rate and an air flow rate step disturbance), the flue gas temperature gradually decreases, and the fluctuation of the instantaneous temperature change rate gradually flattens out. The instantaneous temperature change rate for pre-gasification combustion after the disturbance occurs is greater than that for traditional combustion, indicating a more sensitive response to the disturbance. The moment when the instantaneous temperature change rate reaches 0 is taken as the time required for the system to return to a steady

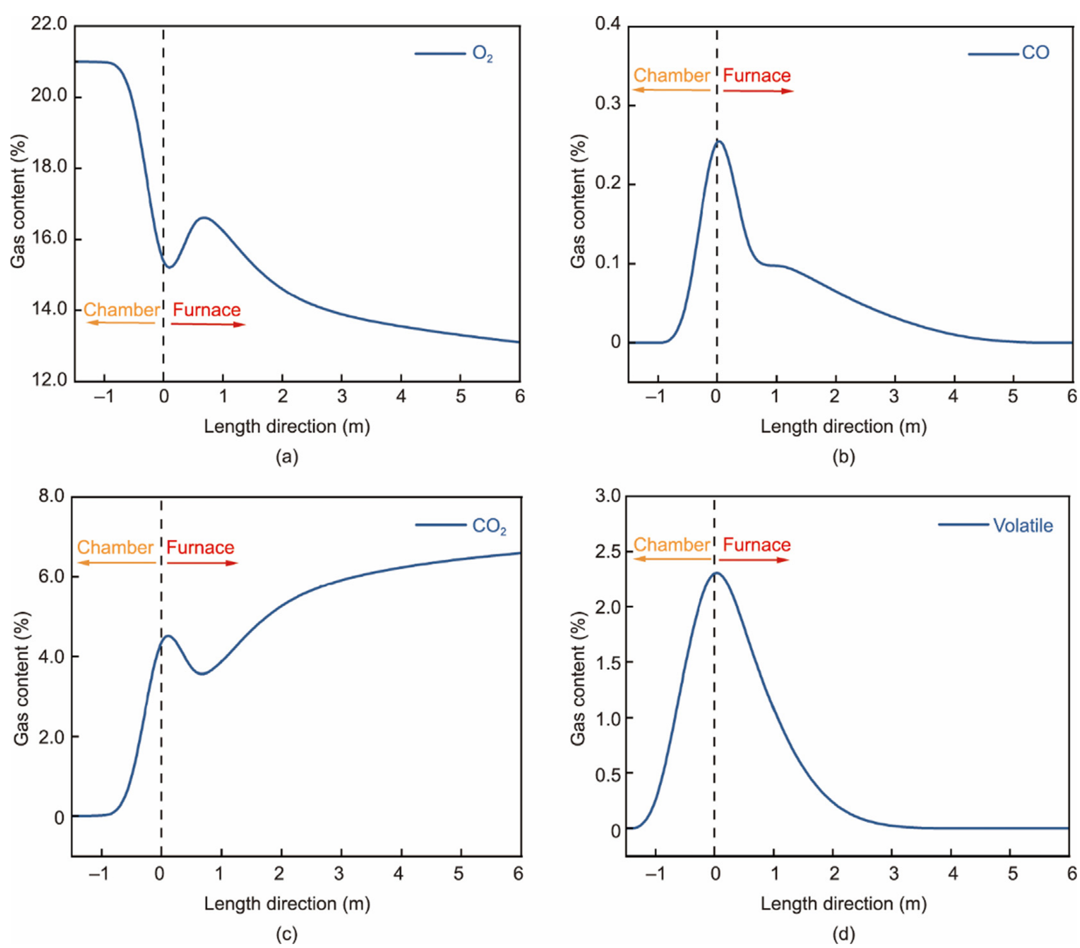

Fig. 7. Gas content along the horizontal furnace under a 10% load: (a) O_2; (b) CO; (c) CO_2; (d) volatile.

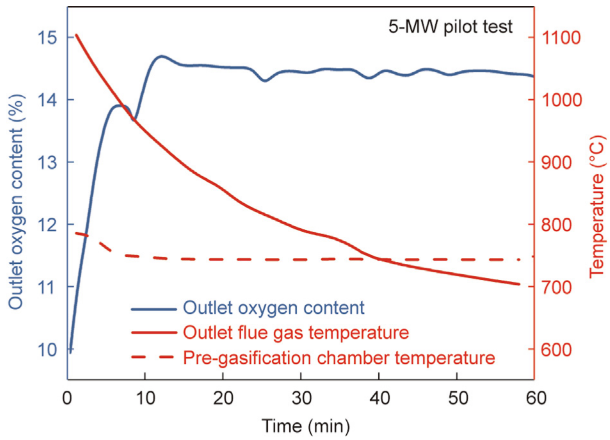

Fig. 8. Parameter monitoring during continuous 1 h operation under a 9% load.

state after the disturbance. As shown in Fig. 10(b), the traditional combustion takes 15.3 s to return to a steady state, while the pre-gasification combustion takes only 9.2 s—about 40% less time. This analysis suggests that the pre-gasification combustion first converts the pulverized coal in the pre-gasification chamber, so the reactants entering the furnace are mainly high-temperature gas-phase fuels such as CO, H_2, and CH_4. Compared with the slow reaction process of coal, the homogeneous reactions are faster and easier to carry out. In addition, the small size of the pre-gasification chamber compared with the furnace results in faster dynamic response characteristics when disturbances occur, further affecting the reaction in the furnace.

The process of a step change from a 30% load to a 50% load was compared for both combustion modes. As shown in Fig. 11, pre-gasification combustion still has a faster response rate as well as a shorter stabilization time. While traditional combustion takes 33.6 s to reach a stable state, pre-gasification combustion takes only 14.3 s, a reduction of about 57%. It is worth noting that a step-increase disturbance at low loads requires a longer stabilization time than a step-decrease disturbance at high loads. This is due to the low combustion temperature under a low load, which makes it difficult to support the timely reaction of the added fuel. This phenomenon suggests that the flexibility of the load-up process is more difficult to regulate.

3.3. Improving the flexibility of the combustion side of coal-fired boilers with the pre-gasification burner

3.3.1. Application of the pre-gasification burner in an industrial boiler

A retrofit design of a single pre-gasification burner was carried out for a 29-MW coal-fired industrial boiler, and the combustion was simulated. As shown in Fig. 12, there is a significant difference

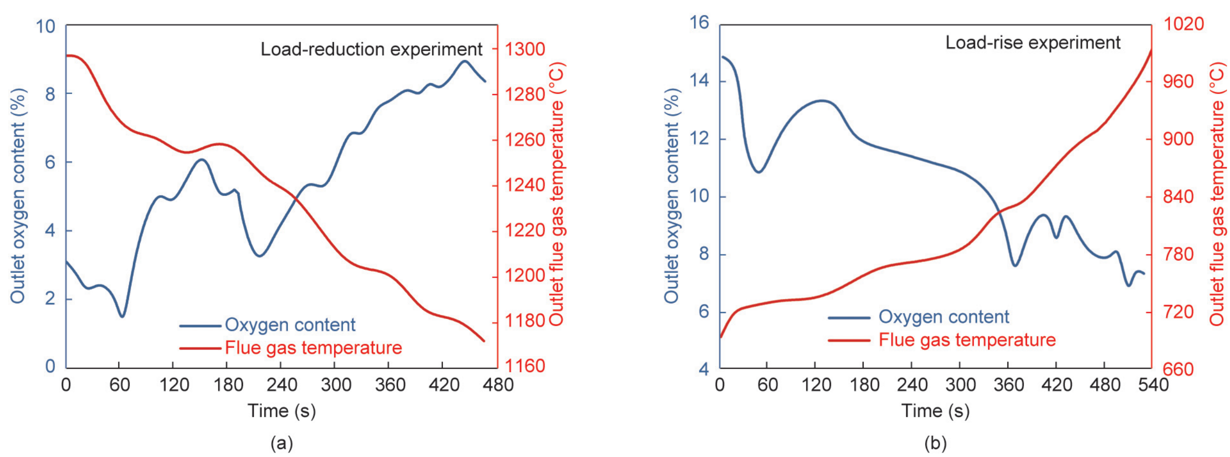

Fig. 9. Parameter monitoring of a rapid (a) load-reduction process and (b) load-rise process.

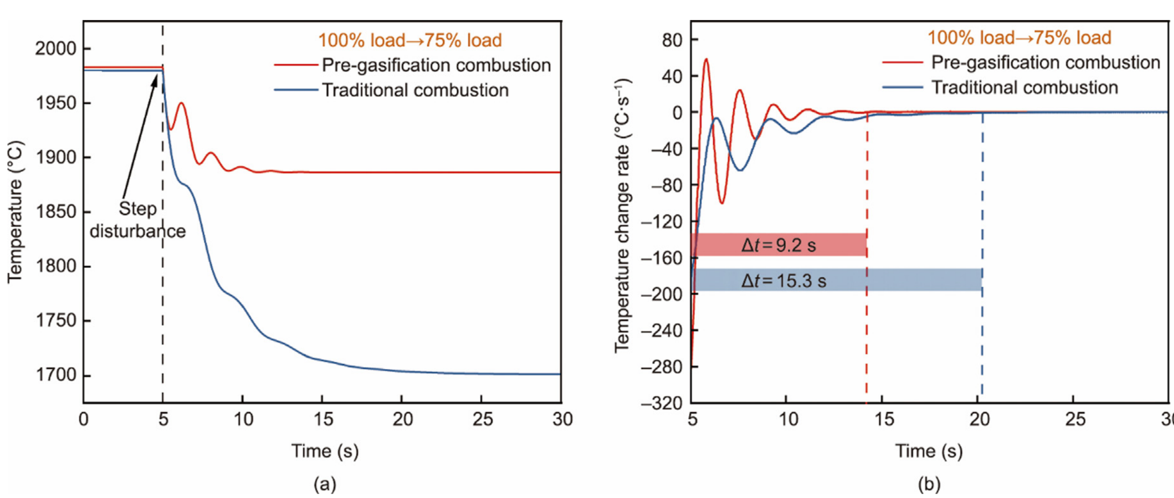

Fig. 10. Dynamic characterization of the flue gas temperature after a step disturbance from a 100% load to 75% load.

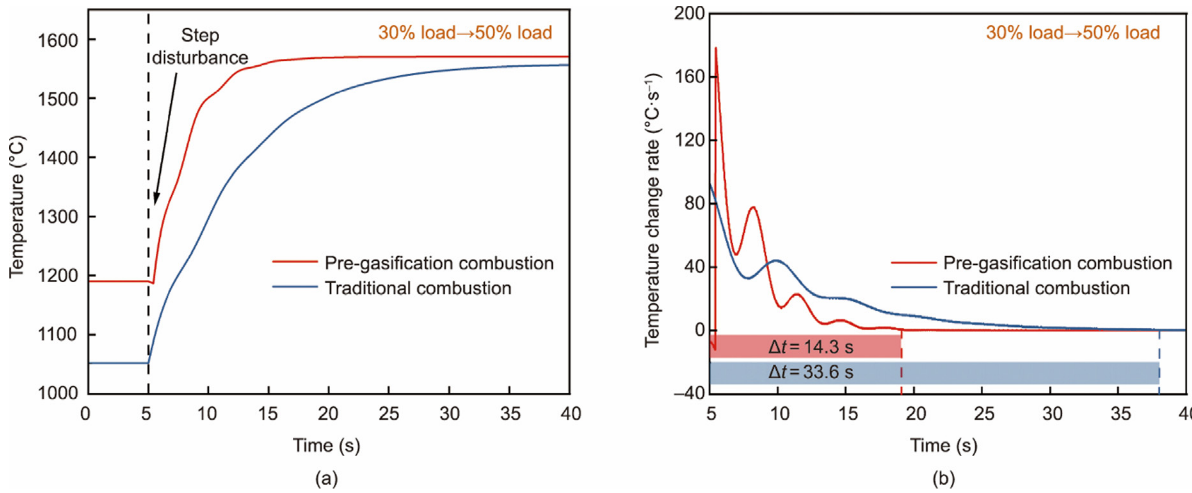

Fig. 11. Dynamic characterization of the flue gas temperature after a step disturbance from a 30% load to a 50% load.

in the combustion in the furnace under different loads. Under a full load as shown in Fig. 12(a), there is no obvious flame inside the furnace, and the overall temperature distribution is uniform, indicating that flameless combustion is achieved. As the load decreases, the temperature at the rear of the furnace decreases, and a high-temperature zone forms toward the front of the furnace (Figs. 12(b) and (c)). Under 15% load as shown in Fig. 12(d), the high-temperature zone forms in the pre-gasification chamber and develops inside the furnace. Flame stability can be ensured by the reaction inside the pre-gasification chamber. Under a 15% load, the flue gas temperature at the furnace outlet is 725 °C, which still meets the heating demand.

To verify the deep peaking potential of the pre-gasification burner on an industrial boiler, a minimum steady-combustion load test was carried out on a 29-MW boiler. Table 4 shows a comparison of the test results with the simulation results. The results show that the pre-gasification burner can support steady combustion under a load of about 15%, with stable furnace operation. The relative errors between all the test data and simulation results are within 10%, indicating the accuracy of the simulation model.

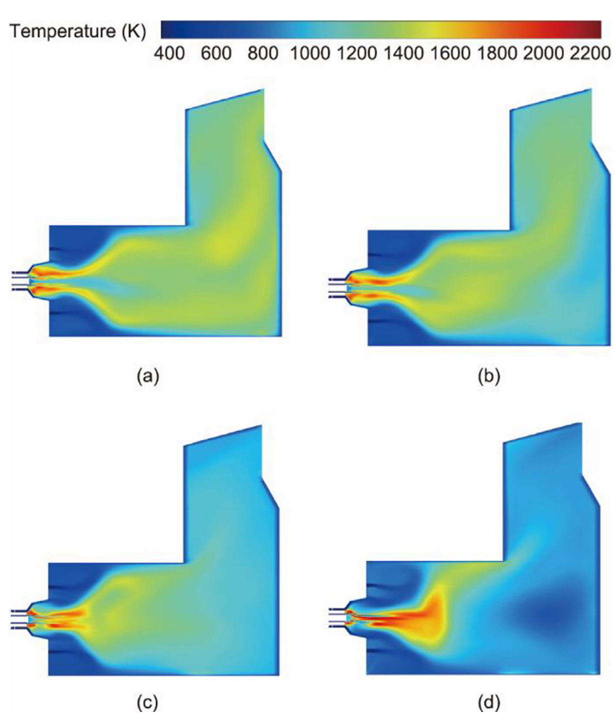

Fig. 12. Temperature distribution of the 29-MW industrial boiler under different loads: (a) 100%; (b) 50%; (c) 25%; (d) 15%.

After modifying the necessary geometrical parameters, a dynamic response characterization of the combustion side of the industrial boiler was carried out using the Aspen Dynamics model. Fig. 13 shows the dynamics of the flue gas temperature and the components on the combustion side under coal, air flow, and overall step disturbances from a 100% load to a 75% load. The disturbance is added at t = 5 s. As shown in Fig. 13(a), the combustion temperature decreases gradually. Under the step disturbance of the coal flow, both the CO and CO_2 concentrations of the flue gas are reduced, and the O_2 concentration is increased due to the overall reduction of C and N involved in the reaction. The rate and magnitude of the decrease in combustion temperature are greater under the step disturbance of the air flow. The decrease in air flow results in a shortage of O_2, such that a large amount of fuel cannot be fully reacted. The CO concentration in the exit flue gas increases rapidly, while the CO_2 concentration decreases. A comparison of the stabilization time of the flue gas temperature under the three disturbances shows that the stabilization time under the overall disturbance is the shortest. The stabilization time under the air flow disturbance is much greater than those under the other two disturbances. This result indicates that the effect of air flow variation on the combustion side is the most significant during a load-changing process. Drastic and continuous fluctuations in combustion temperature would be caused by sharp changes in the air flow, affecting the combustion stability. The load-changing process can be made more rapid and steady by matching the simultaneous changes in the coal and air flow.

3.3.2. Application of a pre-gasification burner in a power station boiler

For large coal-fired power station boilers, the difficulty of improving the boiler flexibility lies in the deep peaking capability. A pre-gasification burner retrofitting program was designed for a 330-MW tangential coal-fired power station boiler. The original burner was retained, and a retrofit layer was added. Two pre-gasification burners were positioned on the front and rear walls of the boiler, in an opposed arrangement. In the vertical part of the furnace, the retrofit layer was located between the two direct-current (DC) burners in the main combustion zone. Fig. 14 shows the temperature distribution of the boiler before and after the retrofit under a 20% load. Before the retrofit, the boiler was

Table 4
Comparison of the test and simulation results for the 29-MW boiler.

Item	Minimum load	Flue gas temperature	Oxygen content at outlet	NO_x emission at outlet
Experiment result	14.7%	702 °C	9.79%	236.2 mg·m^{-3} (6% O_2)
Simulation result	15.0%	725 °C	9.72%	217.7 mg·m^{-3} (6% O_2)
Relative error	2.01%	3.27%	0.72%	7.83%

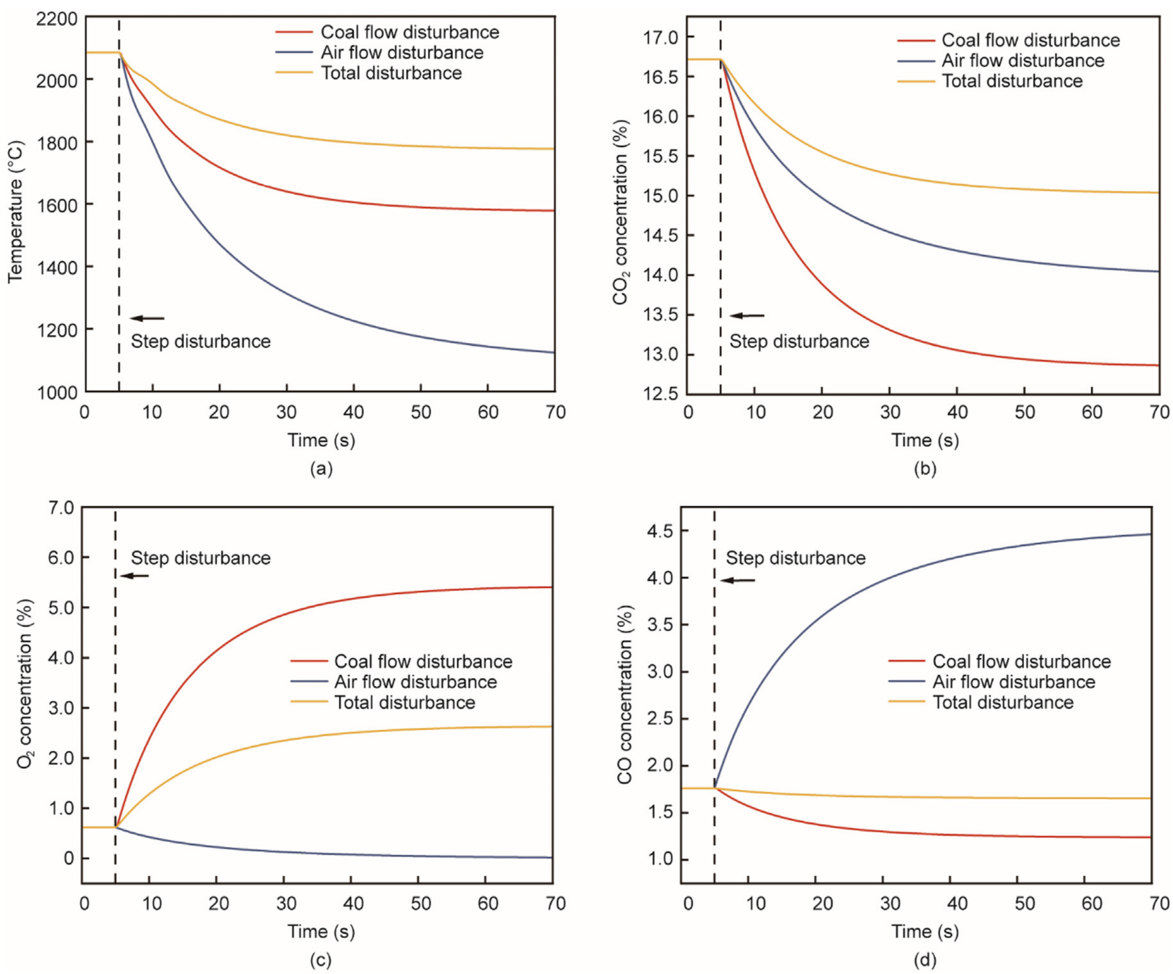

Fig. 13. Dynamic characterization of a pre-gasification burner after different disturbances from a 100% load to a 75% load: (a) temperature; (b) CO_2; (c) O_2; (d) CO concentration.

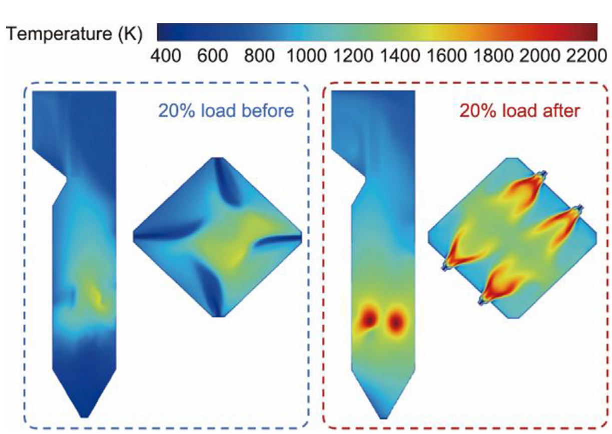

Fig. 14. Temperature distribution under a 20% load before and after the retrofitting of a 330-MW tangential boiler.

equipped with a one-layer DC burner; under low loads, it was difficult for the boiler to form a stable flame at the burner layer, and there was significant temperature loss inside the furnace. After the retrofit, a significant high-temperature zone was formed in the burner layer. A stable flame was formed by the pre-gasification burners, allowing the furnace to maintain a uniform temperature distribution.

The average cross-sectional temperature distribution along the furnace height under a 20% load before and after the retrofit was further compared. Fig. 15 shows that, under a 20% load, the temperature of the furnace before the retrofit drops significantly. The temperature in the main combustion zone does not exceed 1100 K, indicating that combustion fails to develop. In this case, the deep peaking capability of the boiler is limited. After the pre-gasification burner is activated, the average cross-sectional temperature at the height of the retrofit layer reaches 1350 K—an increase of about 260 K. Meanwhile, the temperature at the height

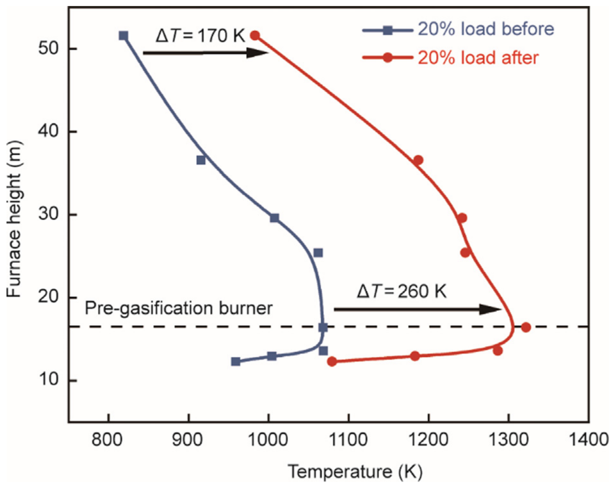

Fig. 15. Temperature distribution along the furnace height under a 20% load, before and after retrofitting.

of the superheater rises by about 170 K. Thus, the pre-gasification burner significantly improves the deep peaking capability of the power station boiler.

4. Conclusions

This study proposed a high-concentration pulverized coal pre-gasification burner. Combustion improvement by means of pre-gasification was first studied at the laboratory scale. Subsequently, a pre-gasification burner was installed on a pilot platform and an industrial boiler, and simulations and experiments were carried out. Finally, a burner modification program was proposed, and simulations were explored based on a power station boiler. The potential application of the pre-gasification burner to increase the flexibility of thermal power plants was comprehensively discussed. The main conclusions are presented below:

(1) After pre-gasification, the pulverized coal consists of gasification gas and high-temperature char. The gasification gas is rich in the flammable components CO, H_2, and CH_4. The outlet temperature of the gasified fuel can reach 850 °C, allowing the fuel to burn quickly and stably after coming into contact with air.

(2) Pre-gasification burners offer better flexibility than traditional swirl burners. The simulation results showed that, under a 10% load, stable combustion could be ensured on a 5-MW pilot platform equipped with a pre-gasification burner, whereas the fire was extinguished in a traditional swirl burner. Furthermore, the pre-gasification combustion mode of the pilot platform had a faster response under load step disturbance. Compared with traditional combustion, pre-gasification combustion reduces the stabilization time by 40% to 60%.

(3) The 5-MW pilot test results showed that the pre-gasification burner achieved stable combustion under an ultra-low 9% load when burning bituminous coal. The temperature inside the pre-gasification chamber was maintained at 750 °C, forming a stable root fire source. A fuel load variation rate of 10% min^{-1} was supported by the pre-gasification burner in the 15%–100% load range.

(4) The simulation and experimental results showed that the pre-gasification burner can be applied in an industrial boiler, and stable combustion under a 15% load can be supported. Furthermore, the modification of a pre-gasification burner on a power station boiler can support stable combustion under a 20% load and improve the deep peaking capability.

CRediT authorship contribution statement

Hanlin Zhang: Writing – original draft, Visualization, Software, Data curation. **Yixiang Shu:** Software, Investigation, Data curation. **Xuebin Wang:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Xu Zhou:** Supervision, Project administration, Funding acquisition. **Weicheng Li:** Supervision, Project administration, Funding acquisition. **Haiguo Zheng:** Methodology, Conceptualization. **Houzhang Tan:** Writing – review & editing, Supervision, Resources, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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