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A mode transition strategy from air to oxyfuel combustion in a 35 MW coal-fired power plant boiler

Zixue Luo[†], Wenfeng Cheng, Bo Wu, Yongchun Zhao, and Junying Zhang

State Key Laboratory of Coal Combustion, School of Energy and Power Engineering,
Huazhong University of Science and Technology, 1037 Luoyu Road, Hongshan District, Wuhan, Hubei 430074, P. R. China

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Abstract−The atmosphere under the conditions of a coal combustion reaction in the furnace is the factor that makes the most significant difference during mode transition from traditional air to oxy-fuel combustion. The flue gas is adopted as the primary air and secondary air for pulverized-coal conveying and the support of combustion; it has a high carbon dioxide concentration during the oxy-fuel combustion. The air-leakage reduces CO_2 enrichment and leads to thermal NO_x production. A control strategy of this shift operation is conducted in a 35 MW oxy-fuel combustion power plant boiler by adjusting the furnace pressure, regulating the recirculation rate of the flue gas and amending the oxygen concentration in the inlet stream. The furnace pressure can be changed smoothly and stabilized at a micro-positive level as the pressurized air flow is monitored at a suitable range. The combustion-supporting flue gas is modified by the oxygen content in the furnace outlet, and the circulation rate of the flue gas verifies the regulation process. Results show that the CO_2 concentration in the flue gas can be rapidly increased along with the increment of furnace pressure and oxygen in the inlet stream; then, this procedure gradually becomes flattened. The CO_2 content in the flue gas correlates with the recirculation rate of the flue gas and oxygen concentration in the inlet stream. The two operation parameters should be maintained at a high CO_2 concentration in a range from 0.6-0.7 and 29.5%-30.5%, respectively. Sampling analysis shows that SO_2 and NO_x emissions were 26 (±1.5) mg/MJ and 90 (±11.7) mg/MJ in air condition, 14 (±0.4) mg/MJ and 34 (±1.6) mg/MJ in oxy-fuel combustion; the burnout rate, mechanical losses of incomplete combustion and the unburned carbon rate remained similar at these two stable combustion modes. This mode transition scheme should provide a reference for monitoring and diagnostics, design and operation control of an oxygen-enriched pulverized-coal combustion power plant boiler.

Keywords: Mode Transition, Oxy-fuel Combustion, Control Strategy, Pulverized Coal, Power Plant Boiler

INTRODUCTION

Greenhouse gas (GHG) emissions mainly result from fossil-fuel combustion and are considered to contribute to global warming. The best way to reduce carbon emissions is to develop a new coal combustion technology with carbon capture ability. Oxy-fuel combustion is one of the more effective carbon capture and storage (CCS) techniques, due to its ability to effectively enrich flue gas with high CO_2 concentration [1] and to reduce pollutants from coal-fired power plants [2]. This combustion technology can easily be applied to retrofitting existing boilers [3]. Thus, the merits of oxy-fuel combustion technology have become one of the most promising methods proposed to meet the demands of reducing greenhouse gases emissions, and several demonstration projects have been built [4,5]. Compared with traditional air combustion power plant boilers, a complete oxy-fuel combustion system includes a boiler, air separation unit (ASU), compression and purification unit (CPU), and recycling flue gas (RFG) devices. These components provide oxygen for pulverized-coal combustion, the purifying and compressing of flue gas, and the drawing out of clean recycling flue gas from the CPU for CO_2 storage.

The significant discrepancy between traditional air and oxy-fuel combustion in the furnace is variable. Combustion characteristics, such as coal ignition and burnout [6], flame stability [7], combustion products [8], and convection and radiation heat transfer [9,10], are varied as RFG mixes with oxygen instead of ambient air. In addition, an oxy-fuel combustion operation has been carried out [11-13] by regulating the recirculation rate of the flue gas and the oxygen concentration in the inlet stream (the proportion of oxygen in the primary and secondary air) in recent years.

The establishment of an accurate dynamic model and an efficient control strategy are particularly important for the design, operation and optimization of the oxy-fuel combustion power plant boiler [14]. Snarheim [15] used the frequency domain method to analyze the robustness of the control system, and discussed the conception, criterion, control strategy and optimization of the simulation process. Guedea [16] provided a method of controlled recirculation of the flue gas and verified the method in a 90 kW oxy-fuel combustion fluidized-bed boiler. Kuczynski [17] presented a dynamic model for an oxy-fuel power plant. An oxy-fuel combustion unit had been shown to have improved flexibility and load response with appropriate control structures. Edge [18] took a novel

[†]To whom correspondence should be addressed.
E-mail: luozixue@hust.edu.cn
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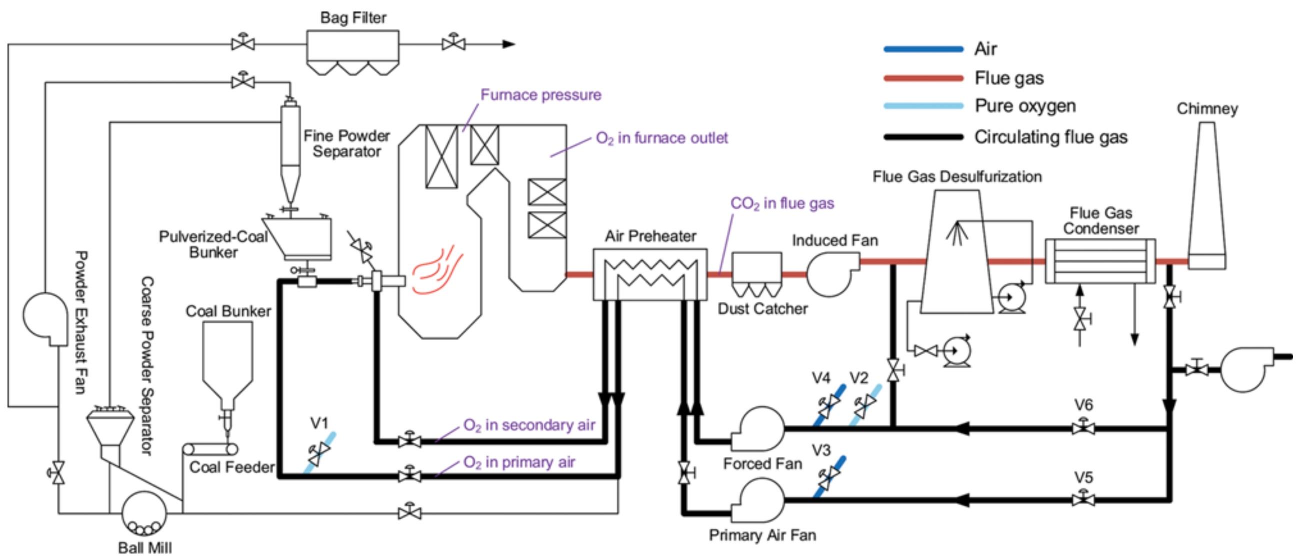

Fig. 1. Sketch of the oxy-fuel combustion system.

approach to the oxy-fuel combustion model by simulating the full-size power plant, and assessed the response of the entire process between the boiler and steam turbine. Jin [19] presented a conceptual design of a dynamic model and control system in a 600 MW oxy-combustion pulverized-coal-fired boiler, which could be used for a wide range of engineering tasks, such as load change, planned disturbances, mode switching and comparison of control strategies.

In this study, we have established a set of dynamic models and control strategies based on in-situ operational data for the smooth transition from conventional air-fired to oxy-fuel combustion in a 35 MW oxy-fuel combustion power plant. Experiments were developed to demonstrate the transition operation from air combustion to oxy-fuel combustion, and furnace pressure was switched from negative to micro-positive to illustrate that the enrichment of CO_2 in the flue gas reduced air-leakage. Moreover, optimal operation parameters were examined by regulating the oxygen in the inlet stream and the recirculation rate of the flue gas for high CO_2 concentration enrichment. This work should provide an ideal transition strategy from air to oxy-fueled combustion for a pulverized-coal-fired power plant boiler.

EXPERIMENTAL FACILITY AND CONTROL DESIGN

The study object is a 35 MW oxy-fuel combustion power plant boiler, which consists of an ASU, a boiler and combustion unit (including a set of burners and pulverized coal feeding devices), a flue gas cleaning apparatus (FGC), a primary air fan, a forced fan, an induced fan, regulating valves and a distributed control system (DCS). The steam boiler, which was manufactured by Dongfang Boiler Works, is a natural circulation, medium-temperature and medium-pressure drum-type boiler. The cross section is 4,733 mm× 3,533 mm, and the height of the furnace is 15,150 mm. Three swirling burners were mounted in the mid-front wall, and the primary air and secondary air were used for conveying pulverized-coal and supporting combustion. To achieve precise oxygen concentration control for primary and secondary air, and to facilitate flow organization and combustion in the furnace under conditions of oxy-fuel combustion, the full pre-mixed method of injecting oxygen into the RFG was adopted. There is an air separation unit (ASU) provided by Sichuan Air Separation Plant Group. The oxygen production can be up to 6,400 Nm^3/h, and the purity of oxygen reaches over 97.5%. The facility is equipped with a liquid oxygen tank (the volume is 600 Nm^3) to meet the requirements of the maximum output and load adjusting for oxy-fuel combustion. The pure oxygen stream from the ASU is split into a duplex path; one channel is for the preheated primary air flow, and the other is for an oxygen flow mixed into cold secondary circulating flue gas.

Fig. 1 shows the overview of the oxy-fuel combustion power plant. A portable infrared flue gas analyzer was applied with the type of Gasboard-3100P to obtain CO_2 (range from 0 to 100%) and O_2 (range from 0 to 25%) concentration, which are based on non-dispersive infrared sensor (NDIR) technology and electron capture detector (ECD), respectively. The furnace pressure sensors (range from −3,000 Pa to +3000 Pa) were installed at the right and left side of horizontal pass of the furnace outlet. The steam pressure sensors were set on the steam header ranging from 0 to 5 MPa. Under the conditions of air combustion, primary and secondary air derived from the atmosphere, the oxygen injection valve (V1 and V2) and the recycled flue valve (V5 and V6) are closed entirely, and the air inlet valve (shown as V3 and V4) is open. The primary air and secondary air are transported by a primary air fan and a forced fan, respectively. After air pre-heat treatment, the primary air is used for conveying pulverized-coal, and the secondary air is for supporting combustion. The flue gas is emitted into the atmosphere after a series of purifying processes is performed by the FGC.

The ASU should be started up before the operation is switched from air to oxy-fuel combustion, which provides the oxidant. There are two pure oxygen injection locations: the primary flue gas oxygen injection point V1 is set behind the air preheater, and the other oxygen injection V2 is arranged in front of the forced fan, between the RFG and the air inlet. When V1, V2, V5 and V6 are gradually opened, V3 and V4 should synchronously close to establish the

Table 1. Characteristics of coal for in-situ experiment (air dried basis)

Proximate analysis/wt%				Ultimate analysis/wt%					$Q_{LHV,ar,}$ MJ/kg
M_{ad}	A_{ad}	V_{ad}	FC_{ad}	S_{ad}	N_{ad}	C_{ad}	H_{ad}	O_{ad}	
0.41	30.50	18.93	50.16	0.75	0.45	58.23	3.41	6.94	22.04

CO_2/O_2 atmosphere during this mode transition. The RFG stream was taken from the exhaust gas, and the flue gas condenser was used to cool down the flue gas. The combustion state could be adjusted with the regulating flow of the recycling flue gas and the oxygen concentration in the inlet stream.

Proximate and ultimate analyses of the coal are shown in Table 1. The excess air ratio α is 1.2, the primary air ratio r_1 is 0.25, and the secondary air ratio r_2 is 0.75 in this in-situ experiment for a steady combustion. The stoichiometric ratio between the actual and theoretical oxygen is defined as the excess oxygen ratio $\lambda_{(O_2)}$ under conditions of oxy-fuel combustion. Typically, $\lambda_{(O_2)}$ can be set up as 1.15 in the oxy-fuel combustion process to achieve a similar air combustion atmosphere in the furnace.

Combustion control from coal and air feeding to a qualified steam is a complicated process in utility boilers. Compared with traditional air combustion, the oxy-fuel combustion control scheme can be parsed out into furnace pressure control, and recirculation rate of flue gas and load control, which is different from traditional air combustion. The three control schemes are derived from their inherent strategies. As shown in Fig. 2, the transfer functions G_1 and G_2 should be verified in every control loop for leading/lag time adjustment. In this loop, N, E1, D, E_2 and P represent the setting input signal, the deviation signal between the measured value and the setting signal, the disturbance signal and the measured value of controlled variable. These symbols mean different things in different subsystems. The transfer functions of G1 and G2 can be identified by data acquisition, and these models can also be verified for the accuracy and leading/lag time. The process should adjust the variation impact of the disturbance.

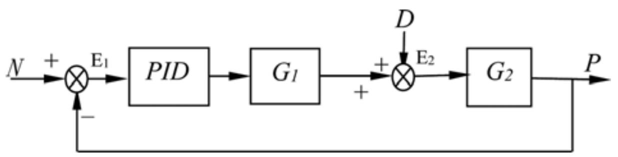

Fig. 2. Verification in the original control loop for oxyfuel combustion.

1. Furnace Pressure Control

The oxy-fuel combustion adopts a micro-positive pressure control strategy, which can reduce air-leakage and thermal NO_x production. The inlet stream volume flow measured by flowmeters acts as a feed-forward signal into the furnace pressure control loop in the DCS. The furnace pressure could be switched gradually from negative to micro-positive pressure and then stabilized around the setting value by regulating the inlet stream flow and the air-draft amount. The inlet volume flow consisted of recirculated flue gas, air from the atmosphere and pure oxygen from the ASU.

A two-input single-out system model is used for furnace pressure control: the inputs are the inlet stream flow and the inlet pressure of the induced fan (instead of the air volume), and the output is the furnace pressure. Based on the experimental data and iterations of the Gauss-Newton algorithm, the model can be described as:

$$G_1(s)=\frac{-0.04633s+0.02364}{s^2+1.323s+0.9432}e^{-2s},\ G_2(s)=\frac{0.1012s+0.4438}{s^2+1.558s+1.28}e^{-5s} \quad (1)$$

Fig. 3 shows the comparisons between the model prediction

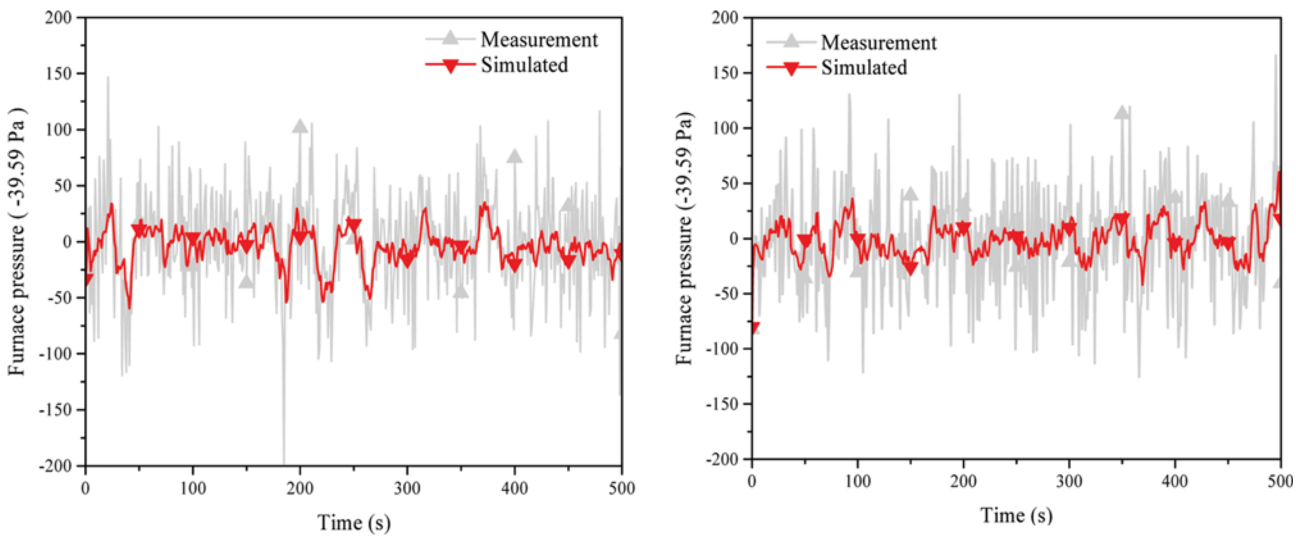

Fig. 3. Furnace draft control calibration.

and the in-situ experiment in the control loop.

2. Recirculation Rate of Flue Gas

Under conditions of oxy-fuel combustion, the oxygen needs to be injected into the recirculating flue gas from the ASU for the combustion of the pulverized-coal, and the recirculation rate of the flue gas (η) is the main parameter for the combustion and modulation of the furnace atmosphere. There is an inevitable lag time from fuel feeding to burn out, and the control circuit adopts a cascade control method to keep the carbon/oxygen ratio in a reasonable range. The recirculation rate of the flue gas η and the oxygen in the inlet stream $\alpha_{(O_2)}$ are the critical factors that influence heat transfer in the constant combustion that is occurring in the furnace.

The structure of the control model focuses on recycling flue gas and oxygen injection as the two inputs, and the recirculating rate of the flue gas is the output. The model may be derived as:

$$G_1(s)=\frac{1.439\times10^{-5}s+1.769\times10^{-8}}{s^2+1.528s+1.317\times10^{-3}},\quad G_2(s)=\frac{1.877\times10^{-6}s-3.648\times10^{-8}}{s^2+1.4s+3.053\times10^{-10}} \tag{2}$$

A comparison of simulation and validation results is shown in Fig. 4. It can be found that the control model has high precision.

3. Load Control

The fuel supply device comprises one pulverized-coal bunker and three impeller coal-feeders connected by three swirling burners. As mentioned, the demand signal is the leading time, and the pulverized-coal feeding can be controlled by adjusting the frequency of the coal-feeders to control the unit load. The relation between the quantity of coal powder supply and the speed of coal-feeders is shown in Fig. 5, and an appropriate linear formula is derived as Eq. (3):

$$y=0.16546\times f_{feeder} \tag{3}$$

The model structure of load control contains pulverized-coal feeding and a quantity of water (including regular water and de-superheating water), and the output is the main steam volume flow. The transfer function may be derived as Eq. (4):

$$G_1(s)=\frac{-8.715\times10^{-3}s-5.865\times10^{-4}}{s^2+3.921\times10^{-3}s+8.143\times10^{-5}}e^{-39s},\quad G_2(s)=\frac{2.729\times10^{-3}s-1.44\times10^{-5}}{s^2+4.361\times10^{-3}s+2.327\times10^{-4}}e^{-84s} \tag{4}$$

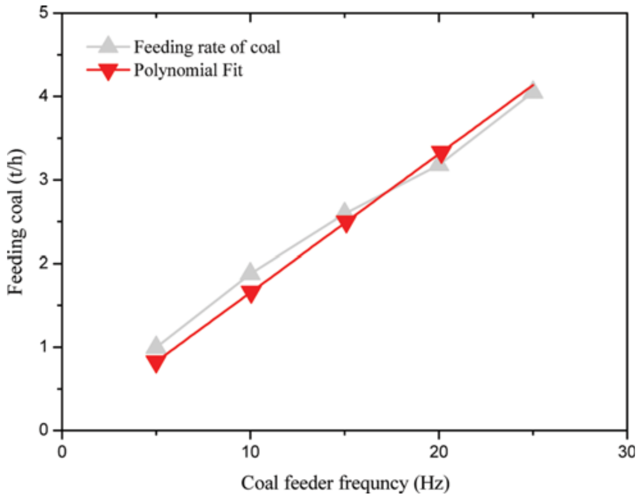

Fig. 5. The relationship between fuel feeding and frequency.

The model verification has been carried out. As shown in Fig. 6, a comparison between the experimental data and the simulation results shows agreement.

EXPERIMENTAL RESULTS AND DISCUSSION

1. Shift Operation from Air to Oxy-fuel Combustion

The switch operation from traditional air combustion to oxy-fuel combustion involves the process of reducing air and increasing oxygen injection to adjust the oxygen in the inlet steam in an

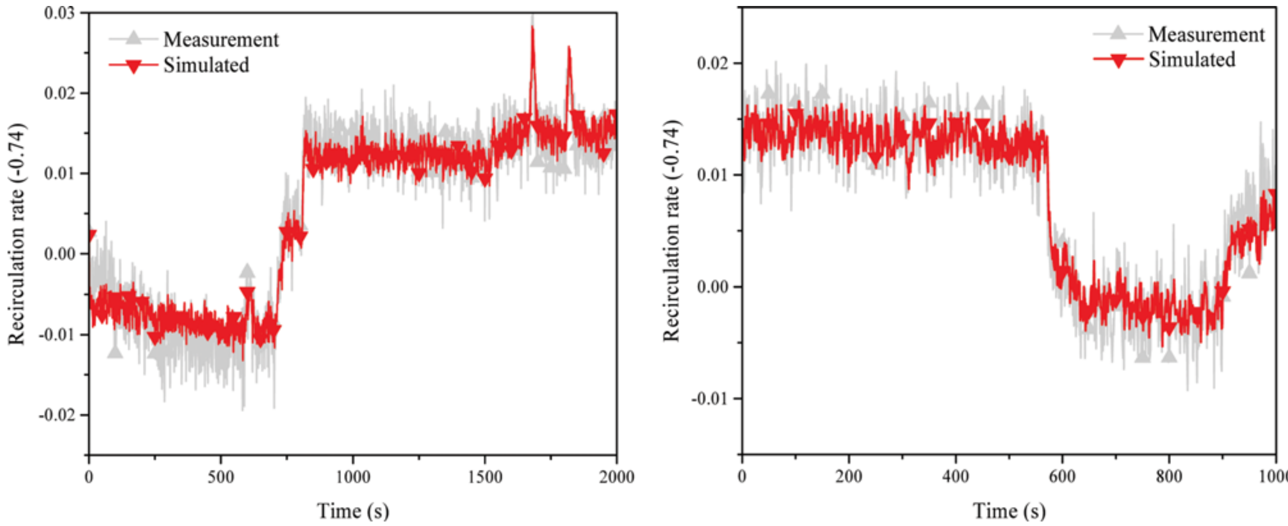

Fig. 4. Model verification of recirculation rate of flue gas.

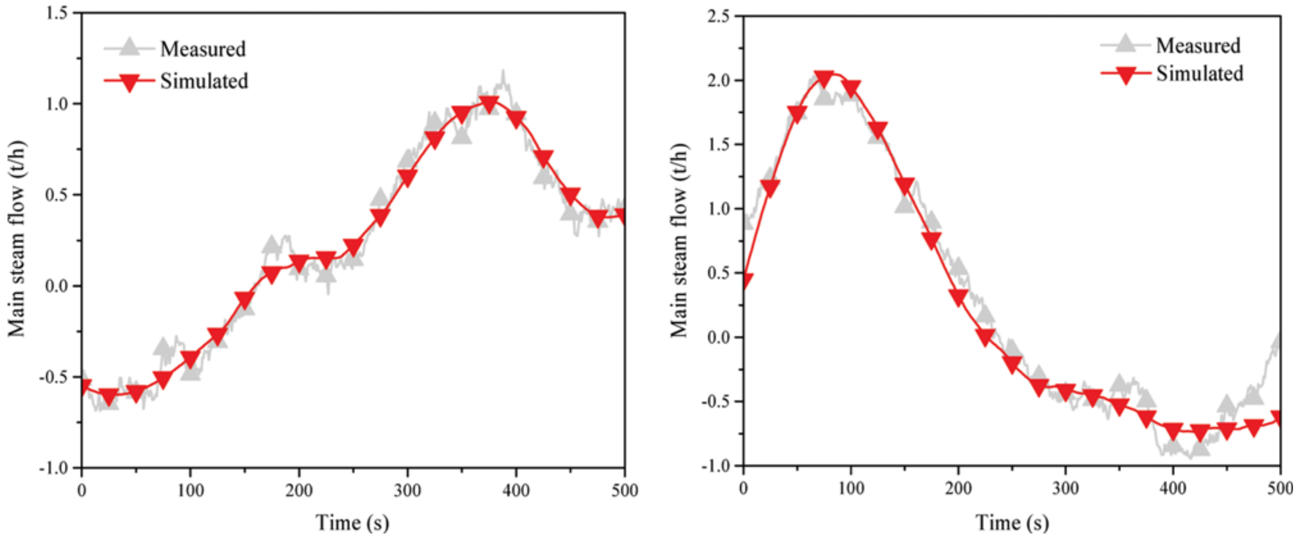

Fig. 6. The correction of load control scheme.

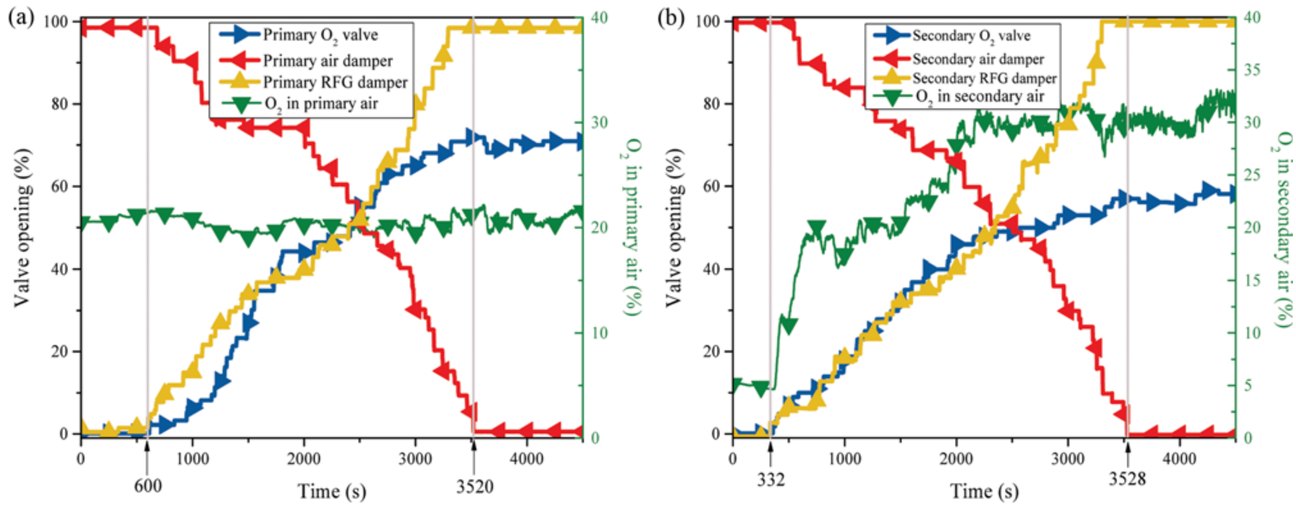

Fig. 7. Shift operation in primary and secondary air.

oxygen-enriched circumstance. The transition of the modes of primary and secondary air is performed by recirculating the flue gas and injecting oxygen, respectively.

The oxygen concentration in the primary air flow is set at 21%, which is the same as the amount found in ambient air, to ensure the safety of conveying the pulverized-coal during the shift operation. The regulation of the oxygen concentration in the secondary air flow is designed as a concentration-variable control, which can be adjusted via the oxidants in the inlet stream to achieve coal burnout and ideal heat transfer inside the furnace. Fig. 7 illustrates the levels of oxygen in the primary and secondary air and also depicts the valve opening associated with the shift operation. As shown in Fig. 7(a), the primary air damper-opening was decreased from 100% to 0%, while the primary oxygen-injection valve and the primary RFG damper were gradually opened over a period of 2,980 seconds. The oxygen concentration in the primary air flow can be stabilized at a valve setting of 21% during the primary air switching; this is controlled by regulating the volume of the oxygen injection flow. As illustrated in Fig. 7(b), when the secondary air damper is closed, the secondary oxygen injection valve and the secondary RFG damper are opened over a period of 3,196 seconds, and the whole process is completed in 3,528 seconds. During this process, the oxygen in the secondary air rose from 4% to approximately 30% to meet the needs of the unit load. The measuring point of the oxygen in the recirculated secondary air is set between the downstream of the secondary oxygen injection point and the upstream of the secondary recycling flue gas [Fig. 1]. Therefore, there is also a lag time during the shift operation in the oxygen concentration of the RFG.

The parameters of the furnace and steam-water side that are most important during the shift operation from traditional air combustion to oxy-fuel combustion are illustrated in Fig. 8. The furnace pressure was maintained at −80 Pa in this procedure, and the shift operation can maintain the following conditions of stability:

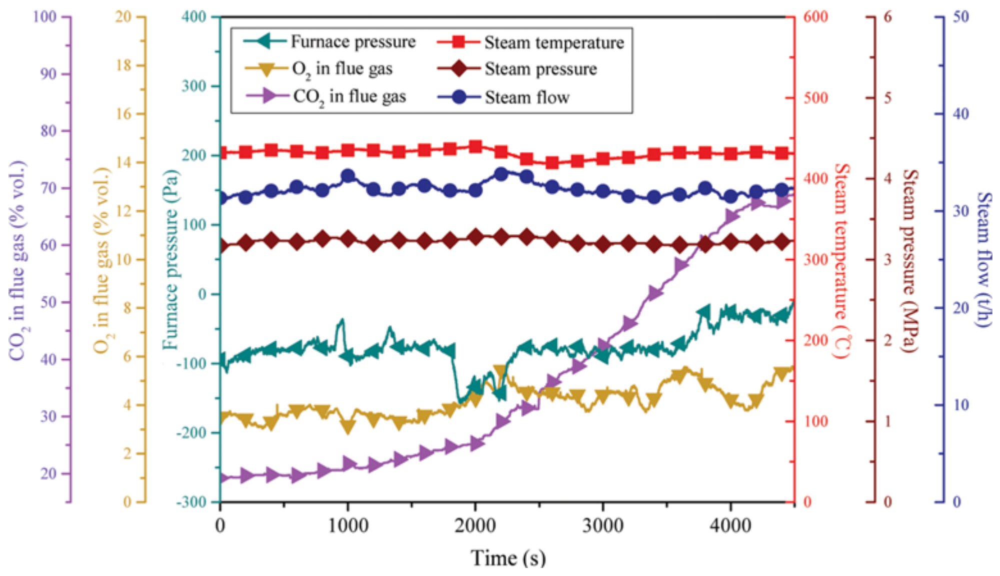

Fig. 8. Change of main parameters under mode shifting.

the oxygen in the flue gas is kept at approximately 4% for the appropriate C/O ratio; and the steam temperature, pressure and flow are 428 °C, 3.2 MPa and 32.5 t/h, respectively. The CO_2 in the flue gas increased gradually from 20% to around 60% at first, and then it rose from 60% to 68.8%, which raised the furnace pressure and reduced air-leakage at a certain load above.

2. Adjusting Furnace Pressure for CO_2 Enrichment

Experiments were performed under oxy-fuel conditions to validate the furnace pressure from negative to micro-positive to increase the CO_2 concentration in the flue gas. As shown in Fig. 9, the furnace pressure changed from −80 Pa to 40 Pa. The furnace draft control process was divided into several stages during the shift operation. The five cases, from stage 1 to stage 5, comprise a negative pressure period as well as four other micro-positive pressure atmospheres. Under the negative pressure situation, the CO_2 concentration in the flue gas could be accumulated from 56.92% to 71% as furnace pressure increased from −80 Pa to 0 Pa; this accumulation was due to a significant reduction in the leakage of ambient air into the furnace. During the periods of micro-positive pressure, the CO_2 concentration in the flue gas could reach to 76% as furnace pressure rose from 0 Pa to +40 Pa. Compared with the negative pressure in the furnace, the CO_2 concentration in the flue gas would change smoothly in a micro-positive pressure atmosphere. These results are due to the limited air-leakage in the micro-positive pressure flue gas as well as the benefits of the enriched-oxygen modulating the inlet stream.

Fig. 10 depicts the variation of some important parameter in the furnace side (CO_2/O_2 in flue gas and furnace pressure) and in steam-

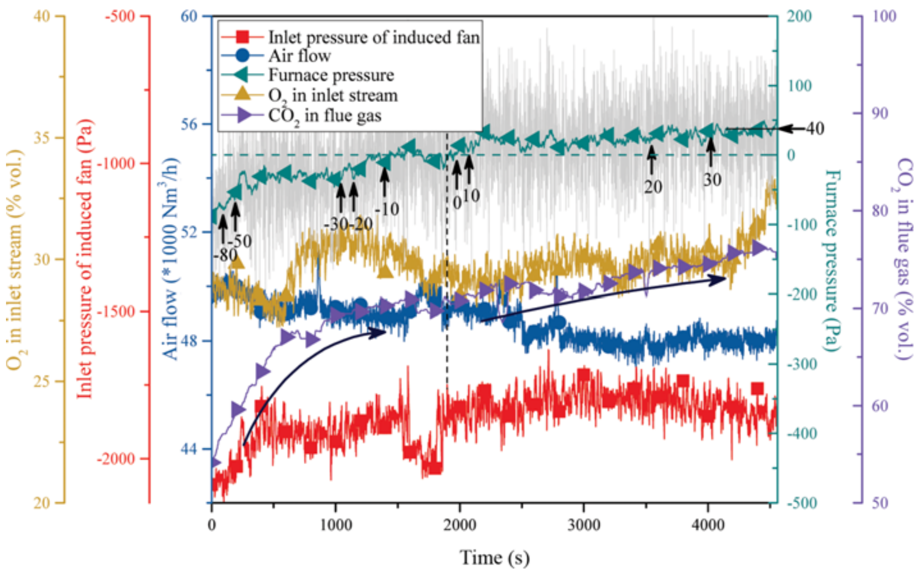

Fig. 9. Regulation in furnace pressure for high CO_2 concentration.

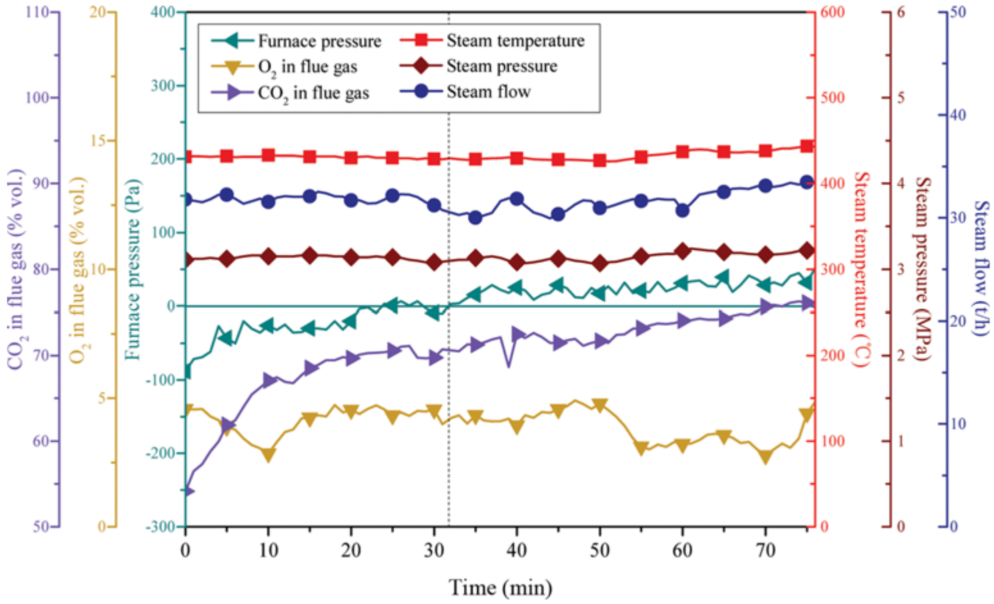

Fig. 10. Parameters in stable combustion and steam-water side during shift operation.

water side (temperature, pressure and steam flow) during the mode transition experiment. The figure was split by the dotted line with negative stage (left) and micro-positive pressure stage (right). The O_2 in flue gas was used to monitor the combustion efficiency of pulverized coal, and an excessive O_2 in flue gas indicated the heat loss caused by coal combustion. The fine furnace pressure control process could be manipulated without any disturbances on both sides, and the oxygen concentration in the flue gas could be kept at approximately 4%, and CO_2 concentration increased as furnace pressure from negative to micro-positive with suitable oxygen. Moreover, steam temperature, steam pressure and steam mass flow could be stabilized at 430 °C, 3.1 MPa and 31 t/h, respectively.

3. Oxygen Concentration in Inlet Stream and Circulation Rate of Flue Gas

The pulverized-coal oxygen-enriched combustion conditions in a furnace could be adjusted by regulating the oxygen-injection in the inlet stream ($\alpha_{(O_2)}$) and the recirculation rate of the flue gas (η). Experiments were developed for a 35 MW oxy-fuel combustion boiler to verify the two parameters for the CO_2 concentration enrichment of the flue gas. As shown in Fig. 11, there is a strong mapping relationship among the CO_2 concentration in the flue gas, the oxygen content in the inlet stream and the recirculation rate. The oxygen concentration in the inlet stream and the circulation rate of the flue gas should be maintained in the range of 29.5%-31.5% and 0.65-0.70 for high carbon dioxide concentrations. The CO_2 concentration could reach 82.72% as $\alpha_{(O_2)}$, and the values of were set at 29% and 0.68 in this in-situ experiment.

Fig. 12 presents the transition procedure of CO_2 and oxygen with $\alpha_{(O_2)}$ in the flue gas. It can be seen that $\alpha_{(O_2)}$ and the oxygen content in the flue gas have tendencies similar to those in section A. This

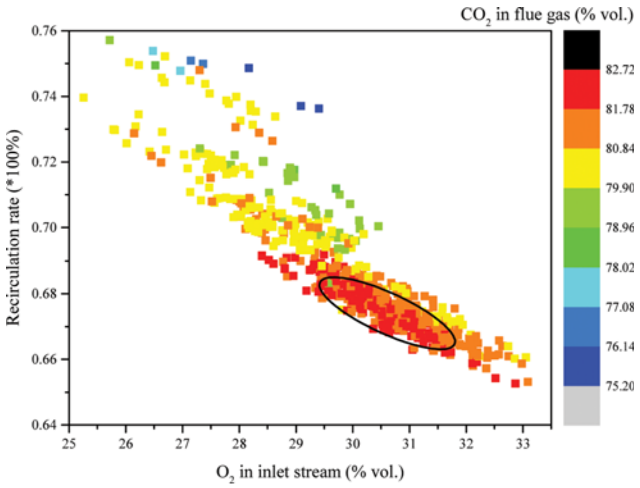

Fig. 11. Correspondences of recirculation rate and oxygen content in flue gas.

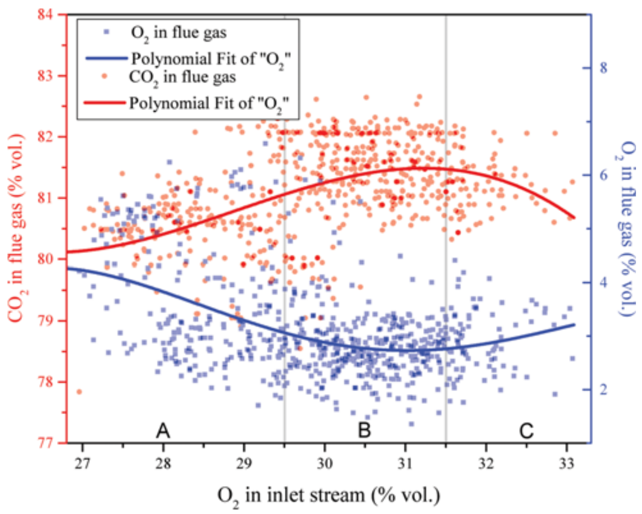

Fig. 12. Different operation sections for CO_2 concentration.

Table 2. The combustion parameters during mode transition

	O_2 concentration (% vol.)			CO_2 in flue gas (% vol.)	Recirculation ratio (*100%)	Flame temp. in furnace (°C)	Furnace pressure (Pa)	Flue gas flow (Nm^3/h)
	Primary air	Secondary air	Furnace outlet					
Air combustion	21	21	3.51	19.65	/	772.18	−42.01	26876.66
Oxy-fuel combustion	21	30	3.5	80.85	0.68	830.45	41.54	25051.76

is because the increased oxygen in the inlet stream can lead to the improved burnout rate of the pulverized-coal. The CO_2 concentration in the flue gas should decrease in the presence of oxygen content in excess of 31.5% (section C). Whereas, high CO_2 concentration in the flue gas and a moderate oxygen concentration in the furnace outlet can be obtained when the oxygen content in the inlet stream ranges from 29.5%-30.5% (section B).

The combustion parameters are shown in Table 2. The oxygen content in the primary air and the furnace outlet was nearly unchanged, but the oxygen content in the combustion-supporting secondary flue gas rose approximately 10%. The furnace pressure reached 41.54 Pa; at this pressure, the CO_2 concentration reached a high of over 80% from 19.65%. The furnace outlet temperature experienced only minor changes, and the total flue gas was reduced a small amount. The discharge quantity of NO_x was 34 (±1.6) mg/MJ in oxy-fuel condition and 90 (±11.7) mg/MJ in air condition. There was no N_2 in furnace chamber in oxy-fuel combustion; therefore, thermal NO_x was reduced and only fuel nitrogen NO_x. Meanwhile, the higher CO_2 concentration in furnace could react with char to form CO, which should lead NO_x to N_2. The SO_2 emission was 26 (±1.5) mg/MJ in air condition and 14 (±0.4) mg/MJ in oxy-fuel combustion, the desulfurization efficiency of FGD was more than 95.2% in the different situations. The particulate matter was 15.7 g/Nm^3 in air condition and 21.78/Nm^3 in oxy-fuel combustion at the entrance of ESP (Electrostatic precipitator), and it was due to the recirculation flue gas: Although it can be absorbed by flue gas condenser, the recirculating flue gas should carry small particles from the closed combustion system. The mechanical losses of incomplete combustion were 4.597% and 4.691% in air and oxy-fuel combustion, respectively. Sampling analysis showed that the burnout rate and the unburned carbon rate remained similar at the different stable combustion modes in the experiments. This mode transition scheme is determined for the benefit of the monitoring, design and operation of an oxygen-enriched pulverized-coal combustion power plant boiler.

CONCLUSIONS

Dynamic control strategies of a 35 MW coal-fired oxy-fuel combustion boiler have been presented based on in-situ experiments and the model identification method. The principles were verified by online regulating procedures. The mode transition from traditional air combustion to oxy-fuel combustion reveals that this shift operation can be conducted in conditions of a specific micro-positive pressure in the furnace, a specific oxygen content in the inlet stream and a reasonable recirculation rate of the flue gas; these factors combine to produce a high CO_2 concentration.

Comparative analysis illustrated that the CO_2 concentration in flue gas could be significantly increased from 20% to 60% in conditions of oxy-fuel combustion, and it was further improved, from 60% to 82.72%, by switching furnace pressure to 40 Pa. The oxygen content in the inlet stream and the recirculation rate of the flue gas are the two most important factors for CO_2 enrichment. These two parameters should be stabilized in the range of 29.5%-31.5% and 0.65-0.70, respectively, to produce enriched CO_2 concentration in the flue gas of over 80%, with an ideal relationship between combustion in the furnace side and the evaporation system. Sampling analysis showed that the burnout rate, mechanical losses of incomplete combustion and the unburned carbon rate remained similar at the different stable combustion modes. This real-time demonstration platform may provide tangible guidance for boiler design and diagnostics in an oxy-fuel combustion operation unit.

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