Experimental study on ignition characteristics of pulverized coal under high-temperature oxygen condition

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Abstract. The high-temperature oxygen ignition technology of pulverized coal, which can replace the oil gun and achieve oil-free pulverized coal ignition by mixing the high-temperature oxygen and the pulverized coal stream directly, was proposed and a relevant ignition experimental system was built. The ignition characteristics of pulverized coal under high-temperature oxygen condition were investigated: the ignition process was described and analyzed, the influence of relevant parameters on the pulverized coal stream ignition were obtained and analyzed. The results showed: when the oxygen heating temperature is over 750 °C, the pulverized coal stream could be ignited successfully by high-temperature oxygen; increasing the pulverized coal concentration, primary air temperature and oxygen volume flow rate or decreasing the primary air velocity is helpful for the ignition and combustion of the pulverized coal stream.

1. Introduction

With the rising price of fuel oil, a consensus has been obtained on cutting down electricity generation costs by reducing fuel oil consumption in pulverized coal-fired utility boiler ignition. Various pulverized coal oil-free ignition technologies have become a focus of research. Sugimoto et al. [1] investigated the stabilization of pulverized coal combustion assisted by plasma, which proved that the plasma ignition technology is practical and feasible in the field of utility boilers ignition. Kanilo et al. [2] studied the ignition and combustion of pulverized coal using a microwave plasma assisted burner and gave some suggestions for the improvement of burner performance. In China, Zhang et al. [3] described the application of plasma ignition technologies in bituminous coal-fired boilers. Plasma and microwave assisted burners both have problems such as short lifetime and needing regular maintenance. Li et al. [4] proposed the induction-heating ignition of pulverized coal, which is also called high-temperature air oil-free pulverized coal ignition. In induction-heating ignition, the high-temperature air is the main and most reliable heat source for pulverized coal ignition.

Compared with conventional air combustion, oxygen-enriched combustion has a lower ignition temperature and higher combustion intensity and flame temperature. In addition, with the development of pressure swing adsorption technology [5-6], the cost of oxygen generation has been reduced greatly.

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Therefore, the application of oxygen-enriched combustion technology in the pulverized coal ignition of utility boilers is feasible and acceptable. The main principle of pressure swing adsorption technology [7-8] is that the adsorption capacity of adsorbents (zeolites) on nitrogen is higher than oxygen under certain pressure, so oxygen and nitrogen can be separated. The operation process of pressure swing adsorption includes air inflation, pressurization and adsorption and vacuum desorption. The entire process is carried out under conditions of normal temperature, so the cost of oxygen generation is low: the power consumption of 1 Nm$^3$ oxygen generation is approximately 0.35–0.45 kW-h. Preliminary calculations indicate that compared with oil ignition, the cost of oxygen ignition is cheaper at only 30–40% that of oil ignition[9-10].

In this paper, the high-temperature oxygen ignition technology of pulverized coal, which can replace the oil gun and achieve oil-free pulverized coal ignition by mixing the high-temperature oxygen and the pulverized coal stream directly, was proposed and a relevant ignition experimental system was built. At the same time, the ignition characteristics of pulverized coal under high-temperature oxygen condition were investigated.

2. Technical design philosophy of ignition device

The basic technical design philosophy of high-temperature oxygen pulverized coal ignition is summarized as follows: Pulverized coal is ignited directly in the primary air-coal mixture by mixing high-temperature oxygen as secondary air. This can improve the temperature and oxygen concentration of the flow. Thus for both high-temperature oxygen and air pulverized coal ignition, the main feature is to use the high-temperature combustion-supporting gas as the main heat source for pulverized coal ignition[11-12]. Compared with high-temperature air pulverized coal ignition, high-temperature oxygen pulverized coal ignition has more advantages. First, the heating gas volume is reduced substantially because of the same oxygen supply. The heating equipment thermal power and corresponding costs are also reduced. Second, with increase in oxygen concentration, the ignition temperature and corresponding ignition heat of the pulverized coal stream decrease, so difficulties in ignition are also reduced[13-14]. In addition, the combustion and flue-gas temperature of the pulverized coal stream increases sharply under oxygen-enriched conditions, so the radiation and convection heat transfer in the flow field is enhanced greatly. Meanwhile, the combustion efficiency of pulverized coal will also increase close to the efficiency of oil combustion, so the stabilization of pulverized coal ignition will be enhanced significantly.

To reduce oxygen consumption in ignition, a small special ignition device was designed that acts as a small oil gun for high-temperature oxygen pulverized coal ignition[15]. A schematic of the ignition device is shown in figure 1.
Figure 1. Schematic of high-temperature oxygen pulverized coal ignition device.

Its basic structure is as follows: a central tube for the primary air-coal mixture is located at the center position and a guide cone is arranged in the center tube nozzle. The swirl high-temperature oxygen is ejected through the outer annular channel and swirl vane. The main reason for using this structure is that the combustion intensity and pulverized coal flame temperature increase under oxygen-enriched conditions. The primary air-coal mixture and oxygen therefore need to be supplied separately. The precombustion or premix chamber cannot be used in the ignition device to prevent sparking. The combustion-supporting gas volume is reduced substantially in the high-temperature oxygen pulverized coal ignition, and the gas density decreases with increase in gas heating temperature, so the gas penetration capacity becomes worse. The guide cone is necessary to strengthen the mixing between the primary air-coal mixture and the high-temperature oxygen and then to ensure pulverized coal ignition.

In high-temperature oxygen pulverized coal ignition, the ignition device is ignited by the high-temperature oxygen first, and then the entire pulverized coal burner is ignited by the ignition device torch. After the entire pulverized coal burner is ignited, the high-temperature oxygen can be replaced by ordinary secondary air.

3. Experimental setup

An experimental system was built for high-temperature oxygen pulverized coal ignition. It consists of an ignition device, gas heating system, powder supply system and measurement equipment. The rated thermal power of the experimental ignition device is 0.1 MW.

Primary air and oxygen are heated by two electric heaters of 4.0 kW and 8.0 kW maximum thermal power, respectively. The thermal power of the two electric heaters is controlled by a silicon-controlled rectifier cabinet. Commissioning tests of the electric heaters showed that the adjustable temperature scales of the primary air and oxygen are 20–400°C and 20–950°C, respectively, with relative errors less than 1.0% and 3.0%, respectively. A schematic of the electric heater is shown in figure 2.

Figure 2. Schematic of electric heater.

Pulverized coal is supplied by a screw feeder in a uniform range of 110–270 g/min with a supply error of less than ± 8.0 g/min.

The flame temperatures of experimental ignition were measured using an IR-AHS portable digital radiation thermometer that is a narrowband radiation thermometer for high temperature. The measuring scale of the radiation thermometer is 600–3000°C with a relative error of less than 2.0%.
The radiation thermometer position was fixed during the ignition process (one-sided 1.5 m to the ignition device) to ensure accuracy and repeatability of measured results.

Four pulverized coals, including lignite, bituminous coal, lean coal and mixed coal (lignite: bituminous coal = 3:1) were selected as experimental coal samples. Igniting anthracite coal is difficult in the above experimental ignition device and a special ignition device design was required. The proximate and ultimate analysis of coal samples is given in Table 1[9].

| Coal          | Ultimate analysis (%) | Proximate analysis (%) | Calorific value (kJ/kg) |
|--------------|-----------------------|------------------------|-------------------------|
|              | C_{daf}  | H_{daf}  | O_{daf}  | N_{daf}  | S_{daf}  | M_{ar} | A_{d}  | V_{daf} | Q_{net,ar} |
| Lignite      | 73.00   | 4.85    | 20.30   | 0.89    | 0.96    | 35.4   | 15.2   | 43.0    | 14038     |
| Bituminous coal | 83.11   | 5.69    | 10.00   | 0.82    | 0.38    | 5.5    | 24.0   | 26.0    | 23865     |
| Lean coal    | 87.62   | 3.44    | 2.16    | 1.36    | 5.42    | 6.5    | 26.0   | 13.3    | 23073     |
| Mixed coal   | 75.53   | 5.06    | 17.73   | 0.87    | 0.81    | 27.9   | 17.4   | 38.8    | 16495     |

The four pulverized coals are all ground by an experimental rod mill. The pulverized coal fineness R90 and average particle sizes of the four pulverized coals are shown in Table 2[9]. R90 is the mass percentage of particles that cannot pass through a 90 μm aperture sieve, the average diameters of the coal particles were calculated using the method of reference [16].

| Coal          | R_{90}/(%) | Average diameter(μm) |
|--------------|------------|---------------------|
| Lignite      | 21.7       | 79.1                |
| Bituminous coal | 17.9     | 72.4                |
| Lean coal    | 14.4       | 69.7                |
| Mixed coal   | 15.4       | 67.1                |

4. Ignition process analysis
The design operation condition for the ignition device is a pulverized coal concentration of primary air-coal mixture of 0.8 kg coal/kg air. The volume of oxygen satisfies the combustion stoichiometric ratio and the primary air temperature is 100 °C. The high-temperature oxygen pulverized coal ignition process was studied by increasing the oxygen temperature gradually. The appearance of a stable flame is defined as the point at which pulverized coal ignition is successful. The results show that with an increase in oxygen heating temperature, three different stages appear in the process of pulverized coal stream ignition; the ignition, transition and stable ignition stages.

No ignition occurs when the oxygen heating temperature is below 300 °C, and the pulverized coal stream cannot be ignited completely.

The transition stage occurs when the oxygen heating temperature is 300–450 °C, the entire pulverized coal stream is still not ignited and the pulverized coal stream temperature does not increase visibly, but some pulverized coal particles, especially the small particles, are ignited. A photograph of the particle ignition is shown in figure 3. When the oxygen heating temperature is higher than 450 °C, the number of burning particles increases and black smoke is generated in the pulverized coal stream. The essence of black smoke is a large number of fine coke particles. Due to the heating effect of the oxygen, the pulverized coal particles lose moisture and volatile, then become coke particles and the quality reduce greatly. At the same time, because of the thermal cracking property of the pulverized coal particles, the pulverized coal particles eventually become very small coke particles. These fine coke particles form the black smoke. Sometimes deflagration occurs after generation of the black smoke, and the oxygen heating temperature 450-650 °C is a dangerous range that is prone to deflagration. The main reason for this phenomenon is that with an increase in oxygen heating
temperature, the average temperature of the entire flow field increases and the volatile matter of the pulverized coal is released rapidly in the pulverized coal stream. At the same time, because of turbulence instability and temperature nonuniformity in the flow field, the basic ignition conditions could be satisfied in some parts of the flow field, so the pulverized coal stream can be ignited. However, because the heat quantity is insufficient for igniting the entire pulverized coal stream stably, deflagration appears. Because the lack of heat quantity is the main reason for deflagration, methods such as increasing primary air and oxygen temperatures and preheating the ignition device before ignition are reasonable to avoid deflagration in the ignition.

The stable ignition stage occurs when the oxygen heating temperature is over 750 °C and the pulverized coal stream could be ignited successfully by high-temperature oxygen. The flame color is bright white and the flame temperature is above 2000 °C. A photograph of the flame torch in the stable ignition stage is shown in figure 4.

Figure 3. Photograph of particle ignition in the transition stage.

Figure 4. Photograph of flame torch in the stable ignition stage.

5. Influence of operational parameters

![Graph showing influence of operational parameters](image)

Figure 5. Influence of pulverized coal concentration on minimum oxygen heating temperature.
Figure 6. Influence of pulverized coal concentration on flame temperature.

Figure 5 and 6 show the influence of pulverized coal concentration on the experimental ignition. With an increase in pulverized coal concentration, the minimum oxygen heating temperature for igniting the entire pulverized coal stream successfully decreases and the corresponding flame temperature increases. The main reasons for this phenomenon include the following: first, the average spacing of pulverized coal particles decreases in the pulverized coal stream with an increase in pulverized coal concentration. The heat release becomes concentrated and is helpful for forming a high-temperature area to provide a heat source for pulverized coal ignition. Second, when the thermal power of the ignition device is constant, which means that the coal consumption and heat release remain unchanged in unit time, both the primary air volume and ignition heat for igniting the entire pulverized coal stream decrease with increase in pulverized coal concentration. The pulverized coal stream can therefore be ignited with a lower external heat supplement. In addition, the average oxygen concentration of the flow field increases because of the decrease in primary air volume. The corresponding ignition temperature of the pulverized coal stream therefore decreases and the flame temperature increases.

Figure 7. Influence of primary air velocity on minimum oxygen heating temperature.
Figure 7 and 8 show the influence of primary air velocity on the experimental ignition. With an increase in primary air velocity, the minimum oxygen heating temperature for igniting the entire pulverized coal stream increases. When the primary air velocity is greater than 15 m/s, the pulverized coal stream cannot be ignited steadily even if the oxygen heating temperature is up to 900 °C. The main reasons for this phenomenon are that when the pulverized coal concentration is constant, the heat supplement is insufficient for providing the ignition heat for igniting the entire pulverized coal stream, which increases substantially with increase in primary air velocity. Second, because the primary air temperature is only 100 °C, an increase of primary air velocity decreases both the average oxygen concentration and temperature in the entire flow field and the ignition condition of the pulverized coal stream worsens. With an increase in primary air velocity, the corresponding flame temperature decreases. This is because the residence time and corresponding heat release of pulverized coal particles both decrease in the flow field with increase in primary air velocity. At the same time, the low average oxygen concentration also limits the combustion intensity and flame temperature of the pulverized coal stream in the flow field.

Figure 8. Influence of primary air velocity on flame Temperature.

Figure 9. Influence of primary air temperature on minimum oxygen heating temperature.
Figure 10. Influence of primary air temperature on flame temperature.

Figure 9 and 10 show the influence of primary air temperature on experimental ignition. With an increase in primary air temperature, the minimum oxygen heating temperature for igniting the entire pulverized coal stream decreases. Compared with other parameters, the influence of primary air temperature is more obvious. The main reason is that the heat for igniting the entire pulverized coal stream decreases significantly with an increase in primary air temperature. The corresponding minimum oxygen heating temperature therefore decreases. When the primary air temperature is above 200 °C, some pulverized coal particles, especially small particles, will start to burn in the center tube. When the burning pulverized coal particles are ejected into the flow field and mix with the high-temperature oxygen, both the combustion intensity and heat release rate are enhanced significantly, so the pulverized coal stream is easier to ignite by high-temperature oxygen. However, when the primary air temperature reaches 300 °C, too many pulverized coal particles start to burn in the center tube and deflagration tends to occur in the ignition process. In addition, with an increase in primary air temperature, the corresponding flame temperature increases slightly. This occurs because the average temperature of the combustion-supporting gas increases with increase in primary air temperature in the flow field and the flame and flue-gas temperatures increase.

Figure 11. Influence of high-temperature oxygen heating temperature volume flow rate on minimum oxygen.
Figure 11 and 12 show the influence of oxygen volume flow rate on experimental ignition. Because the high-temperature oxygen is a swirl flow in the ignition, the axial average velocity of high-temperature oxygen is used to indicate the high-temperature oxygen volume flow rate change. With an increase in oxygen volume flow rate, the minimum oxygen heating temperature for igniting the entire pulverized coal stream decreases, but the trend is insignificant. The main reasons for the phenomenon include the fact that when the heat and oxygen supplement are insufficient, mixing of the pulverized coal stream and high-temperature oxygen is the primary factor in controlling pulverized coal stream ignition. With an increase in high-temperature oxygen volume flow rate, the heat quantity, average oxygen concentration and average temperature of the flow field all increase, but mixing does not yield an obvious improvement. In addition, with an increase in high-temperature oxygen volume flow rate, the average spacing of pulverized coal particles increases. This leads to a reduced heat transfer between the pulverized coal particles. On the contrary, the influence of high-temperature oxygen volume flow rate on flame temperature is significant: the flame temperature increases with increase in oxygen volume flow rate. The main reason is that the average oxygen concentration of the entire flow field increases with increase in oxygen volume flow rate, so the combustion intensity and flame temperature of the pulverized coal stream increase.

The required oxygen heating temperature for igniting the lignite is lowest, followed by the mixed coal and bituminous coal, and the highest is the lean coal. The maximum temperature difference between the lean coal and lignite reaches nearly 300 °C. The corresponding flame temperatures show the same trend with the average temperature difference between the lean coal and the lignite being 400–500 °C.

6. Conclusions
In this paper, the high-temperature oxygen ignition technology of pulverized coal was proposed and a relevant ignition experimental system was built. Then the ignition characteristics of pulverized coal under high-temperature oxygen condition were investigated. The results are as follow:

- With an increase in oxygen heating temperature, three consecutive stages appear in the pulverized coal stream ignition: no ignition, transition and stable ignition stages.
- When the oxygen heating temperature is over 750 °C, the pulverized coal stream could be ignited successfully by high-temperature oxygen.
- Increasing the pulverized coal concentration, primary air temperature and oxygen volume flow rate or decreasing the primary air velocity is helpful for the ignition and combustion of the pulverized coal stream.
Nomenclature
Symbol:
- C - mass fraction of carbon (%);
- H - mass fraction of hydrogen (%);
- O - mass fraction of oxygen (%);
- N - mass fraction of nitrogen (%);
- S - mass fraction of sulfur (%);
- M - mass fraction of moisture (%);
- A - mass fraction of ash (%);
- V - mass fraction of volatiles (%);
- Q - calorific value (kJ/kg).
Subscripts:
- daf - dry ash-free basis;
- ar - as received basis;
- d - dry basis;
- net - net value.

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