Applications of Concentrating Photothermal Reactor in Coal Combustion Research

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Abstract. High temperature, rapid heating rate and application potential of special reaction conditions (high pressure, high humidity, corrosive atmosphere) made the concentrating photothermal reactor (CPR) become a hot spot in the thermal experimental research. By the 1930s, the concepts of radical reactions and thermal equilibrium concepts had contributed to the formation of theoretical basis of coal combustion. The application of concentrating photothermal reactor in coal combustion research had provided a new perspective for this traditional subject. This paper introduced the structure and characteristics of concentrating photothermal reactor, and summarized the latest research results on the influence of heating rate, oxygen concentration and biomass addition on coal combustion. A potential frontier research direction - pressurized combustion based on concentrating photothermal reactor was also proposed.

1. Introduction

Coal is the most widely distributed fossil energy resource in the world. Although its status has been replaced by oil, it is still widely used for the huge reserves and the development of utilization technologies. Combustion is one of the earliest coal utilization methods. With the development of clean combustion technology, coal combustion has achieved ultra-low emissions [1]. As the popularization of wind energy, solar energy and other renewable energy, the role of coal-fired power generation in the modern smart grid is also changing. In the future, coal combustion is bound to be refined, intelligent and fast adjustable, which will bring new opportunities and challenges to the in-depth understanding of coal combustion process and the development of new combustion technologies.

Experimental research is the basis of industrial application, but it is difficult to obtain the operating conditions in practical application under the experimental conditions. In the industrial pulverized coal boiler, the ambient temperature could reach as high as 1600 °C, while the heating rate heating rate is up to $10^3 \sim 10^6$ °C/s [2]. However, as shown in Figure 1, conventional experimental apparatus could only
reach the temperature below 1200 °C, and the heating rate is generally lower than 100 °C/min [3].

Researches showed that temperature and heating rate are important parameters affecting coal combustion process [2]. The great difference between the experimental and industrial conditions leads to the lack of reliable data support in guiding the practical applications.

The new coal combustion technologies also bring new challenges to the experimental research. Pressurized combustion, which is carried out in a pressurized boiler with a condensing heat exchanger installed downstream, can improve cycle efficiency through capturing the latent heat of condensation and reduce equipment cost through reducing gas volume. However, in the experimental conditions, it is very difficult to realize the heating under the pressure of 10-100 atm. The traditional reactor needs to bear high temperature and high pressure, which posed a great challenge to the reactor materials [4].

Recently, a new type experimental bench named concentrating photothermal reactor was developed to meet the requirements of high temperature, high heating rate, complex atmosphere and even pressurized experimental studies. In this study, the structure of concentrating photothermal reactor was briefly introduced and the existing applications in coal combustion research were summarized. According to the characteristics of concentrating photothermal reactor, a potential application direction was pointed out.

2. Introduction of concentrating photothermal reactor

2.1 Reactor structure
The schematic diagram of concentrating photothermal reactor is shown in Figure 2. Two concentrating photothermal lamps were used as heat sources to heat the sample set in a transparent quartz reactor. Different from the traditional furnace heated by heating wire, the irradiation from the lamps was concentrated in the area where the sample was located, while the other areas in the reactor were kept at room temperature. At the same time, the energy density of the directional irradiation was very high, which can be used for experimental research at high temperature and high heating rate.

2.2. Multi-information acquisition
Several combustion information could be obtained with the help of modern analytical and testing instruments in the concentrating photothermal reactor, schematically shown in Figure 3.

![Figure 3. Multi-information acquisition in the concentrating photothermal reactor](image)

The detectors included the Balance, IR Temperature Sensor, High Speed Camera and Flue Gas Analyzer. The ignition mechanism could be obtained by the change of pellet temperature, and the gas release law could be obtained by the correspondence of temperature and gas release information. The image information was used to characterize the combustion process, and the gas release rule in different combustion stages could be obtained in accordance with gas release information. The combination of mass loss information and temperature could be used to obtain the information of reaction kinetics. Through the acquisition and analysis of multi-information, the basis of combustion behavior evaluation was enriched, and the combustion phenomenon could be comprehensively evaluated.

3. Existing results on coal combustion in the concentrating photothermal reactor

3.1. Effect of heating rate on the combustion behavior of coal
Figure 4 shows the combustion behavior of coal pellet under different heating rate in the concentrating photothermal reactor. Through the setting of different operating voltage of concentrating lamps, 4 heating rates from 4.02 °C/s to 69.44 °C/s were achieved in the same experimental apparatus. At slow heating rate (4.02 °C/s), coal pellet exhibited “heterogeneous” ignition mechanism, “joint homogeneous” at 15.1 °C/s heating rate, and “homogeneous” ignition mechanism at 52.4 °C/s and 69.4 °C/s heating rate. NO was detected in small concentration (19.9 ± 0.2 ppm/s) only in 52.4 °C/s and 69.4 °C/s heating processes [5]. With the increase of heating rate, the reactions model in the maximum mass loss rate interval changed from 1-dimensional diffusion mechanism model (D1) model to 3-dimensional diffusion mechanism model based on Jander equation (D3) and the corresponding activation energy also decreased from 84.45 kJ/mol to 33.74 and 11.54 kJ/mol.
3.2. Effect of oxygen concentrating on coal combustion

For bituminous coal, based on pyrometric observations under active gas flow in the concentrating photothermal reactor, coal pellets consistently exhibited particular three-stage temperature change process as illustrated in Fig. 5. For the first stage, significant devolatilization process with massive mist generated could be observed in the reactor. However, the oxygen concentration had little effect on the first stage and coal pellet exhibited similar first stage duration regardless the oxygen concentration. For the second stage, no obvious flame was observed at 21% or 30% O₂ during all the three ranks coal combustion for the narrow high temperature zone in the concentrating photothermal reactor, while transient but luminous flames were clearly observed at 40% and 50% O₂ and formed the temperature peaks. For the third stage, char combustion was the main reaction and the the increase of oxygen concentration significantly speed up this process.

3.3. Effect of biomass addition on coal combustion

Figure 6 shows the effect of biomass addition proportion on the combustion process of coal pellet in the concentrating photothermal reactor.
Overall, the addition of biomass significantly reduced the devolatilization delay (the interval between the pellet being irradiated and mist generated in the cinematography) but increased the devolatilization duration (from mist generation to ignition). Correspondingly, the combustion duration decreased with the biomass addition proportion, which was related to the less fixed carbon content in biomass than coal and the more intense combustion of bio-char.

3.4. Potential frontier research direction

According to characteristics of concentrating photothermal reactor, a high pressure reaction tank based on concentrating photothermal heating was proposed for pressurized combustion research as shown in Figure 7. The reaction tank cover (2) with a light source projection window (2.1) was connected to the reaction tank base (1), a reaction chamber (2.2) was set between the air inlet chamber (1.1) and the air outlet chamber (1.2). The reaction chamber (2.2) was provided with a temperature detection mechanism (9) and a pressure detection mechanism (10), stabilizing flow sieves were used to avoid gas shock (11). Due to the concentrated irradiation, the reaction tank could remain at room temperature when the samples were heated to more than 1000 °C. The reaction tank just needed to be pressurized at room temperature, which decreased the requirement of material and made the laboratory grade high pressure combustion research to be possible.

4. Conclusions
The concentrating photothermal reactor was of high heating rate, multiple information acquisition and room temperature chamber, which had been applied in the coal combustion research approaching the
industrial operating conditions. Existing researches had been carried out on the effect of heating rate, oxygen concentration and biomass addition. A high pressure reaction tank based on concentrating photothermal heating was proposed according to the characteristics of concentrating photothermal heating, which could be applied in pressurized combustion research.

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