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A compatible configuration strategy for burner streams in a 200 MW_e tangentially fired oxy-fuel combustion boiler

Junjun Guo[a], Zhaohui Liu[a,*], Fan Hu[a], Pengfei Li[a], Wei Luo[b], Xiaohong Huang[a,*]

[a] State Key Laboratory of Coal Combustion, School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[b] Wuhan Second Ship Design and Research Institute, Wuhan 430205, China

HIGHLIGHTS

- Compatible configuration strategy for tangential oxy-burners is firstly proposed.
- Momentum ratio criterion for tangentially fired oxy-combustion is illustrated.
- Temperature deviation is reduced by using opposing tangential stream technology.
- Temperature deviation and CO level are decreased by approximately 65% and 90%.

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ABSTRACT

The configurations of burner streams under oxy-fuel combustion are highly affected by its increased initial oxygen level. In this study, an air combustion and oxy-fuel combustion compatible configuration strategy for burner streams is proposed for a 200 MW_e tangentially fired boiler, by aid of numerical simulation. Firstly, to achieve a momentum of primary and secondary streams that is similar to that of air combustion, the tertiary stream is switched-off in oxy-fuel combustion. In addition, the opposing tangential primary stream technology is suggested to reduce the gas temperature deviation in the upper furnace, which affects the quality of the steam and the safe operation of the boiler. For the present study, the appropriate opposing tangential angle is 5°–7° relative to the original primary stream design, and the ratio of opposing tangential momentum flow moment should be controlled at the low limit of 0.8 to decrease gas temperature deviation. To achieve a supported flame by the secondary stream, the momentum of the bottom secondary stream in oxy-fuel combustion should not be less than that in air combustion. The study illustrates for the first time that, the key design features of tangentially fired burners under oxy-fuel combustion. Although there are significant changes in the oxidant volume, oxidant composition, and chemical reaction under oxy-fuel combustion conditions, the design criteria of oxy-fuel tangentially fired boiler, in terms of momentum of the primary stream, momentum of the bottom secondary stream, and momentum ratio and momentum flow moment ratio of the secondary stream to primary stream, are consistent with those under air combustion.

1. Introduction

With the consumption of fossil fuels and the large amount of greenhouse gas emissions, carbon capture and storage (CCS) technologies are expected to play a significant role in the prevention of global climate change [1]. Oxy-fuel combustion is one of the leading technologies for CCS. In this combustion, oxygen is diluted with recycled flue gas instead of nitrogen, and as carbon dioxide is highly concentrated in the flue gas, it is easy to remove [2–4].

Oxy-fuel combustion technology can be applied to new or retrofitted power plants. Owing to the uncertainty of the low carbon policy and CO_2 utilization, the feasibility of air combustion should be considered in the oxy-fuel combustion demonstration project. Therefore, the boiler and auxiliary equipment should take into account the requirements of both air combustion and oxy-fuel combustion; this approach is called a compatible or flexible design strategy [5–7]. In order to achieve compatible operation, stable and efficient air combustion and oxy-combustion should be maintained with the same burner system. Simultaneously, heat transfer in the oxy-fuel combustion should be similar to that in air combustion.

A series of studies indicated that the temperature and heat transfer in oxy-fuel combustion can match that in air combustion if proper

* Corresponding authors.
E-mail addresses: zliu@hust.edu.cn (Z. Liu), xh_huang@hust.edu.cn (X. Huang).

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initial oxygen levels are chosen [8–12]. Tan et al. [8] conducted an experiment in a 300 kW_{th} facility and found that, by using an oxidant with an O_2 concentration of 28–35 vol%, the heat flux and temperature in oxy-combustion could match that in air combustion. Andersson et al. [9] studied the Chalmers 100 kW_{th} oxy-fuel facility and found that similar temperature distributions between oxy-combustion and air combustion resulted in similar total radiation intensities. Through a numerical study of utility boilers, Hu et al. [10] found that the highest flame temperature and total heat transfer in oxy-coal combustion with an initial oxygen level of 33 vol% mostly match those in air combustion. Recently, the experimental and numerical investigations on Huazhong University of Science and Technology's Yingcheng 35 MW_{th} oxy-fuel boiler also showed that the temperature and heat transfer in a furnace can match those in air combustion, when the initial oxygen level is approximately 28 vol% [6].

Operating burners under the compatible systems of oxy-fuel and air combustion is challenging, owing to changes in the volume and composition of the oxidant. The results of Hu and Yan [13] showed that the flue gas recycle rate was reduced by approximately 58%, corresponding to an increase in the initial oxygen level from 20 to 35 vol%. Compared with the air combustion, the volume of flue gas is reduced significantly by approximately 40% in the oxy-coal combustion system [14]. The aerodynamics and flame stability of the burner are affected by a decrease in volume of oxidant and flue gas. Accordingly, the configuration strategy for burner streams should be adjusted. Several investigations on flame characteristics and the design principle of oxy-fuel burners have been carried [7,15–17].

Khare et al. [16] found that the predicted ignition was delayed in oxy-fuel combustion, owing to an increase in momentum of the primary stream. Fry et al. [7] discussed the effect of velocity, mass flux, and momentum of the primary stream on the burner characteristics in oxy-fuel combustion. The results showed that flame stability within the quarl was achieved by matching the mass or momentum of the burner primary stream with air combustion. However, matching the primary velocity resulted in a detached flame. Liu et al. [17] investigated the influence of four typical factors on the oxy-flame's stability and shape in a swirl burner, in terms of blockage ratio, swirl number, recycle ratio, and oxygen partial pressure ratio in the primary stream. The swirl number and recycle ratio have a larger influence on the volume of the dark primary core than the blockage ratio and oxygen partial pressure. However, the blockage ratio has the largest effect on the internal recirculation ratio, which can improve the stability of the oxy-flame. By using a perforated plate burner in a confined combustor, Rashwan et al. [18] found that the flammability limits of oxy-fuel combustion were narrower than those of air combustion owing to the adverse effect of CO_2, which decreases the flame's speed. On the basis of fundamental research, several different large-scale swirling oxy-burners (i.e. > 15 MW_{th}) have been applied to several large pilot oxy-coal combustion plants [19–21]. The furnace and burner control, heat transfer properties, and exhaust emissions of the facility have been investigated.

The existing studies of configuration strategy for oxy-burner streams mainly focus on the swirling burner, and few studies have been conducted to study the retrofitting technique or design principle of a tangentially fired burner system for oxy-fuel combustion. Levasseur et al. [22] tested tangentially fired burners in the Alstom 15 MW_{th} boiler simulation facility. Stable combustion can be achieved in both oxy-fuel combustion and air combustion. With the aid of numerical simulation, tangentially fired oxy-fuel combustion has been carried out in several utility boilers [23–26]. Al-Abbas et al. [23] investigated oxy-fuel combustion in a 550 MW_e tangentially fired boiler. The results showed that similar gas temperature and radiative heat transfer could be achieved in oxy-fuel combustion with an initial oxygen concentration of 29 vol%. Yin et al. [25] compared the different gas radiation property models in a 609 MW_e tangentially fired boiler. There was a noticeable difference in the predicted temperature and radiation source term when the different gas radiation property models were implemented to large-scale oxy-fuel combustion simulation. From the numerical investigation of a 200 MW_e tangentially fired boiler, Guo et al. [26] found that stable combustion is achieved by a compatible burner design in both air combustion and oxy-fuel combustion, with a wide initial oxygen concentration range (from 23 vol% to 29 vol%). However, a high CO concentration appeared in the hopper under oxy-fuel combustion with an initial O_2 level of 29 vol%. Zhang et al. [27] carried out experimental and numerical investigations on a 3 MW_{th} tangentially fired oxy-fuel facility. The results showed that a similar flue gas temperature profile was achieved between air combustion and oxy-fuel combustion with initial oxygen levels of 27 vol% and 30 vol% for the dried brown coal and the wet brown coal, respectively. However, the radiative heat transfer and CO emissions were still slightly mismatched between air combustion and oxy-fuel combustion.

The above studies of tangentially fired burners focus on the difference in combustion and heat transfer properties between air combustion and oxy-fuel combustion. The information about the configuration strategy for tangentially fired burner streams is seldom reported for oxy-fuel combustion. It is well-known that tangentially fired burner system is significantly different from swirling burners: the tangentially fired burners are interrelated and dependent on each other, while each swirling burner can operate independently. In addition, flue gas temperature deviation in the horizontal flue gas pass is a frequently occurring problem for tangentially coal-fired boilers, which could result in pipe explosion of superheaters. Therefore, variations in the oxidant volume/momentum and initial oxygen concentration have a larger effect on tangentially fired burners than on swirling burners. It is necessary to investigate the design principle and compatible combustion strategy for tangentially fired burner system under oxy-fuel combustion.

This study is also an important part of our systematic studies on oxy-fuel combustion. The research group at State Key Laboratory of Coal Combustion has carried out in-depth research on oxy-fuel combustion [6,17,26,28–38]. The R&D roadmap of "0.3 MW_{th}-3 MW_{th}-35 MW_{th}-200 MW_e" for oxy-fuel combustion has been practiced [5]. The compatible operation of oxy-fuel combustion and air combustion has been realized with a swirl burner system in the 3 MW_{th} and 35 MW_{th} oxy-fuel combustion power plant [6,30]. Moreover, the prefeasibility study of a 200 MW_e large-scale demonstration has progressed well [26].

The aim of the present study is to investigate the compatible configuration strategy for burner streams for a 200 MW_e tangentially oxy-fuel boiler by validated numerical methods. A modified radiative property model and global combustion mechanisms for oxy-fuel combustion are implemented into the CFD code to simulate a 200 MW_e utility boiler with a series of cases. By focusing on the effects of the change of volume and composition of the oxidant, we develop a compatible configuration strategy for burner streams. As far as we know, this is the first study to discuss a compatible configuration strategy for burner streams of oxy-fuel tangentially fired boilers. The rest of the paper is organized as follows. The basic principle of configuration strategy for tangentially fired burner streams learned from the swirling burners is given in Section 2. The computational details are given in Section 3. On the basis of numerical simulations, the optimal compatible configuration strategy for burner streams is discussed in Section 4. Then, the key design rule of tangentially fired burners in oxy-fuel combustion is proposed in Section 5. Concluding remarks are made in Section 6.

2. Tangentially pulverized coal-fired boiler

2.1. Utility boiler description

The schematic diagram of the 200 MW_e tangentially fired utility boiler is shown in Fig. 1. The boiler is 10,880, 11,920, and 42,500 mm in depth, width, and height, respectively. The heat input of this boiler is approximately 580 MW_{th}, and these simulations are carried out based