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A numerical investigation on flame stability of oxy-coal combustion: Effects of blockage ratio, swirl number, recycle ratio and partial pressure ratio of oxygen

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ABSTRACT

Keeping the flame stable and having the appropriate flame shape is essential in operating an oxyfuel combustion coal fired power plant with CO_2 capture. This is more critical if the boiler is required to operate in full and partial thermal load with varying volume of flue gas recycled. Therefore, in designing the oxyfuel combustion burner, it is important to evaluate the burner stability, shape structure and flame type. This work presents numerical investigation of a burner designed for oxyfuel combustion coal fired boiler. The study evaluated the effects of the blockage ratio, swirl number, flue gas recycle ratio, and oxygen partial pressure in the primary RFG stream on the flame stability, type, shape and structure. The model results were validated against experimental data obtained from a novel oxyfuel combustion burner designed and operated in a 2.5MWt test pilot facility. The model developed for this study incorporated a modified chemical reaction mechanism that allows the addition of CO and Boudouard reaction that is considered significant in an oxyfuel combustion flame. The results show that the stability of an oxyfuel combustion flame is greatly improved by having a moderate to strong internal recirculation zone to produce a Type-II flame; and could also be easily destabilized by a high velocity jet of unburned carbon/char as illustrated by a dark central region emanating from the centre of the burner. Additionally, it could also be illustrated that the swirl number and flue gas recycle ratio have a strong influence to the formation of the central dark region along the centerline of the burner. It could be concluded that maintaining the flame Type-II over the whole range of thermal load should maintain the necessary flame stability appropriate to an oxyfuel combustion boiler.

1. Introduction

As a large amount of carbon dioxide emissions from the fossil fuel combustion accelerates the global climate change, the Carbon Capture, Utilization and Storage (CCUS) technology has been developed in the world. The oxyfuel combustion technology is a promising method for the carbon dioxide reduction (Toftegaard et al., 2010; Wall et al., 2009; Buher et al., 2005).

In a process of oxygen-enriched pulverized coal combustion with recycled flue gas (RFG), it is generally difficult to keep both flame stability and flame type-II structure for oxyburner operating in a different total gas flow rate, especially for the boiler operating in full and partial thermal load with varying volume of recycled flue gas (Roman and Jacques, 1992; Liu, 2012). It is essential for an oxyburner to keep stable flame and maintain appropriate flame shape for operating in air- and oxy-fired combustion. In an oxy-fired mode, the total input volumetric flow rate of the recycled flue gas and oxygen stream is about 50–75% of that in an air-fired mode for an identical thermal load. When the combustion mode changes from an air-fired mode to an oxy-fired mode, the total input volumetric flow rate greatly decreases and it is difficult to maintain both oxy-flame stability and similar stable flame type for this oxyburner (Liu, 2012). Generally, in this mode, the oxy-flame shape and structure is destroyed and the stable oxy-flame structure is changed into an unstable structure.

When the partial thermal load or the reduced recycle ratio is needed for the peak load regulation in the oxy-fired pulverized coal power plant, the total input volumetric flow rate will be more reduced, which accordingly affects both flame stability and sta-

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Nomenclature

CBK	Char burnout kinetic model
CCUS	Carbon capture, utilization and storage
CPD	Chemical percolation devolatilization
DORM	Discrete ordinates radiation model
DPC	Dark primary core
EDC	Eddy-dissipation concept model
FRED	Finite-rate and eddy-dissipation
IFRF	International flame research foundation
IRZ	Internal recirculation zone
RFG	Recycled flue gas
RTE	Radiative transfer equation
SIMPLE	Semi-implicit method for pressure-linked equation
STE	Species transport equation
STM	Species transport model

ble flame structure. In these conditions, the total input gas stream, mainly including recycled flue gas and pure oxygen, generally still needs to be divided into several streams which are injected into the furnace through a novel oxyburner. The stable flame shape (i.e., flame type-II) will be greatly affected and even changed into flame type-0 or I in these different oxy-fired modes (Roman and Jacques, 1992; Liu, 2012). Furthermore, As the input volumetric flow rate is more reduced for the lower partial thermal load, it is almost impossible to maintain the pulverized-coal suspension in the primary stream (i.e., the primary air) and even keep a stabilizing similar flame structure in the furnace. Firstly, in order to keep the pulverized coal in suspension in the gaseous multi-component primary stream, a minimum velocity for this transport gas stream is about 17 m/s (Khare et al., 2008). Secondly, in order to keep the similar and even the same flame shape, it is needed to adjust the momentum ratio of the gas streams.

When the more reduced recycle ratio and the limited transport velocity are used in oxy-fired mode, the original stable flame is significantly destroyed, and it results in a flickering unstable flame (Edge et al., 2011). Generally, the flame type will be changed from the appropriate flame type-II to the flame type-I or 0 (Roman and Jacques, 1992; Liu, 2012) When the central penetrated flame is formed in an oxy-fired mode, it is generally difficult to keep flame stability, and even the ignition delay is brought in the outlet of the burner (Fry et al., 2011). Therefore, the characteristics of oxy-flame stability, structure and shape needs to be further studied. In the past four decades, the air-fired flame stability has been studied and mainly focused on the formation of the internal recirculation zone by a bluff-body or similar objects (Pein et al., 1970; Kundu et al., 1977; Chin and Tankin, 1991; Chen, 1995; Shi et al., 1997; Yasir et al., 2007). However, few studies have been done on both oxy-flame stability and flame structure type for oxyburner. Some previous studies mainly focused on a retrofitting technique or design principle of oxyburner and relative oxy-flame stability (Khare et al., 2008; Fry et al., 2011; Toporov et al., 2008; Heil et al., 2009; Zhang et al., 2011). In these previous studies, five factors, i.e., velocity, mass flux, momentum, momentum flux and the chemical reaction, have been discussed on how to affect these burner characteristics. Khare et al. (2008) and Fry et al. (2011) have discussed the former four factors impacting on oxy-flame stability and ignition delay. They found that the consistent velocity ratio or the momentum flux ratio had an effect on both oxy-flame stability and ignition delay. But the flame stability in an oxy-fired mode was kept under a consistent mass flux or momentum of the primary stream with that in an air-fired mode. A consistent velocity of the primary stream resulted in ignition delay, but a decrease of 13% for this transport velocity brought the same ignition delay and flame stability in the oxy-fired mode as those in the air-fired mode (Fry et al., 2011). Toporov et al. (2008) and Heil et al. (2009) discussed the oxy-flame stability affected by the chemical reactions, namely, the carbon monoxide (CO) oxidation and the Boudouard reaction. They found that the oxy-flame stability was still obtained under 18% oxygen.

It is necessary to have further discussions of oxy-flame stability, shape type and structure affected by oxyfuel combustion operating parameters and oxyburner structure. It is essential to continuously keep both oxy-flame stability and even flame type-II structure for a pilot-scale and industrial oxy-burner in a wide range of operating parameters, especially for a full or partial thermal load and a different recycle ratio.

Therefore, in this work, the characteristics of oxy-flame stability and shape affected by the four important factors are numerically investigated, namely, the blockage ratio, the swirl number, the recycle ratio and the partial pressure ratio of oxygen in the primary stream during the oxy-coal combustion. The center dark primary core, i.e., the center dark region, which is a high velocity jet consisting of unburned carbon, char, etc. species from outlet of oxyburner (Fry et al., 2011), and the internal recirculation zone are discussed by the numerical investigation of oxy-flame stability and structure shape. Some results have been used in oxyburner designs for 3 MWt pilot scale test facility system and 35 MWt demonstrate pulverized coal oxy-combustion power plant in China. The numerical methodology has been validated by our previous work (Liu et al., 2012). This work can help further understand the characteristics of oxy-flame stability and shape in a wide range of operating parameters, which improves design of the industrial oxy-burners.

2. Physical object and characteristics

The swirling oxy-burner (Liu et al., 2012, 2011, 2010) (see Fig. 1) is designed for the 300 kW_t vertical furnace (see Fig. 2) in the State Key Laboratory of Coal Combustion (SKLCC), China. As one of purposes, this oxy-burner is used to investigate the characteristics of the oxy-flame stability and shape. The oxy-burner consists of four parts, i.e., from inner to outer, the flame holder with oil gun, the primary stream (PS, i.e., primary air), the dump ring and the secondary stream (SS, i.e., secondary air), as shown in Fig. 1. The pure oxygen jet pipes are symmetrically installed in the dump ring, as shown in Fig. 1. The dump ring is defined as an annular “bluff body” in the outlet of oxy-burner, which can increase the mixing time for primary stream and secondary stream, and increase the release time of carbon monoxide to benefit nitrogen oxidant reduction reaction, ignition and flame stability.

This test facility system consists of five parts, namely, an oxy-fuel combustion sub-system, a recycled flue gas control subsystem, a pulverized coal transport sub-system, a pure oxygen transport and mixing sub-system and an operating control subsystem. This vertical furnace is a height of 3.5 m and an inner diameter of 0.6m. The 300 kW_t pilot scale test facility is shown in Fig. 2.

3. Mathematical model and procedure

3.1. Flow, combustion, turbulent chemistry model and modified reaction mechanism

In this process of the turbulent diffusion combustion, the gas turbulence is solved by the Reynolds Stress model (RSM). The coal particle burning process generally consists of three phases: the coal particle heating to devolatilize, the volatile mixture burning with volume reactions and the coal char burning with surface reactions. In the species transport equation (STE) model used in this work,