Combustion Characteristics of Oxy-fuel Burners for CO₂ Capturing Boilers*

Joon AHN**, Hyouck Ju KIM*** and Kyu Sung CHOI ***

**Korea Institute of Energy Research, Korea

E-mail:jahn@kier.re.kr

***Korea Institute of Energy Research, Building Energy Research Center

71-2, Jang-dong, Yuseong-gu, Daejeon, 305-343, Korea

Abstract

Oxy-fuel boilers have been developed to capture CO₂ from the exhaust gas. A 50 kW class model burner has been developed and tested in a furnace type boiler. The burner has been scaled up to 0.5 and 3 MW class for fire-tube type boilers. The burners are commonly laid out in a coaxial type to effectively heat the combustion chamber of boilers. Burners are devised to support air and oxy-fuel combustion modes for the retrofitting scenario. FGR (flue gas recirculation) has been tried during the scale-up procedure. Oxy-fuel combustion yields stretched flame to uniformly heat the combustion chamber. It also provides the high CO₂ concentration, which is over 90% in dry base. However, pure oxy-fuel combustion increases NO concentration, because of the reduced flow rate. The FGR can suppress the thermal NO_x induced by the infiltration of the air.

Key words: Oxy-fuel Combustion, Boiler, Burner, CCS (Carbon Capturing and Sequestration)

1. Introduction

Carbon dioxide (CO₂) from the combustion of fossil fuel is recognized as the most significant source of the global warming and the climate change. A quarter of the fossil fuel is consumed by the industrial boilers in Korea, so that they should be the most important items to apply the technology to reduce CO₂ emission. Basically, CO₂ emission from the boilers can be reduced by improving their thermal efficiency. The current state of the art, however, yields the boiler efficiency over 80%, which does not leave much room for the CO₂ reduction. To overcome this limitation, CO₂ from the flue gas should be captured and sequestered ⁽¹⁾.

To capture and/or sequester the CO₂ gas, there are two major approaches. The first one is to use a chemical sorbent such as amine to scrub CO₂ from the flue gas. The second approach is to adopt oxy-fuel combustion, which use the pure oxygen as the oxidizer instead of air ⁽²⁾. When the oxy-fuel combustion is applied, the flue gas should be mainly composed of CO₂ and water vapor. In the flue gas composition, CO₂ can be captured just by condensing the water vapor. Between the two approaches, the oxy-fuel combustion is applied to the industrial boiler in the present study.

Oxy-fuel combustion gives much faster flame propagation, and less flow rate for a given amount of fuel compared to the conventional air combustion. Consequently, the flame becomes smaller and its temperature grows higher ⁽³⁾. To protect the burner from the high flame temperature, the burner for the oxy-fuel combustion is mostly shaped in a coaxial

Fig.1 Oxy-fuel combustion boiler; (a) system schematics; (b) 0.5 MW class experimental setup

structure. The structure is also beneficial to heat the combustion chamber for the existing boiler system, which makes it possible to apply oxy-fuel combustion to a conventional boiler only by retrofitting the burner.

A coaxial jet type burner has been devised in the present study and applied to the CO₂ capturing boiler system, which is illustrated in Fig. 1(a). Natural gas is adopted as fuel and supplied with oxygen to the burner. Boilers in the present study are flame-tube type, which has the horizontal combustion chamber inside the water vessel. The heat in the exhaust gas is recovered by the economizer, which warms the feed water supplied to the boiler. The economizer is designed to recover the latent heat as well as the sensible heat in order to maximize the thermal efficiency and to decrease the energy to sequestrate the CO₂. Flue gas recirculation has been tried to reduce the emission of nitrogen oxides (NO_x) and to be compliant with the retrofit scenario.

The CO₂ capturing boiler system is developed in three steps in the present study. At first, the combustion characteristics of oxy-fuel burner have been studied in a 50 kW class furnace type boiler. Secondly, a 0.5 MW class oxy-fuel boiler has been developed. Detailed combustion and heat transfer characteristics have been investigated for the 0.5 MW class system. Finally, the oxy-fuel burner is applied to a 3 MW class system to verify its feasibility in a large scale industrial application. The heat transfer of the system is presented in the companion paper ⁽⁴⁾ and the combustion characteristics are supposed to be discussed in the present paper.

Nomenclature

D : diameter of combustion chamber, m

r : radial distance from the center axis of the combustion chamber, m
 T : temperature, °C
 x : axial distance from the exit of the burner, m

2. Experimental Setup

Fig.2 Oxy-fuel/ FGR/ air combustion convertible burner; (a) 50 kW; (b) 0.5 or 3 MW

The experimental setup is designed to apply the oxy-fuel combustion to the boiler system to concentrate CO_2 in the exhaust gas as depicted in Fig. 1(b). Natural gas, which is the fuel, is supplied to the burner via a filter. The fuel is fed at the flow rates of 4, 40 and $240 \text{ Nm}^3/\text{h}$, which correspond to the capacities of 50 kW, 0.5 MW and 3 MW, respectively. Oxygen is supplied to the burner by way of an evaporator. FGR (flue gas recirculation) is adopted for 0.5 MW and 3 MW class systems. The flue gas mixed with the oxygen is fed to the burner for the FGR mode. A mixer is installed for the 3 MW class system to mix the flue gas and oxygen. As for the FGR mode, the recirculation ratio is controlled to have the oxygen concentration of 35% in the oxidizer.

Coaxial jet type burners have devised for the present study as shown in Fig. 2. The fuel is injected perpendicular to the oxidizer flow for the 50 kW burner in order to stabilize the flame (Fig. 2(a)). The burner can adjust to the combustion mode, i.e. oxy-fuel and air combustion, by positioning its nozzle ⁽⁵⁾. For the higher capacities of 0.5 and 3 MW cases, the fuel is supplied in the main flow direction, and the oxidizer is supplied through the annular slot around the fuel nozzle. The air and FGR gas with oxygen are fed through two outer slots through swirlers, while the oxygen is injected through the inner slot for the oxy-fuel combustion case.

The burner is connected to the combustion chamber, which is shaped as a cylindrical

Fig.3 Scale-up characteristics of the flames; (a) Load 100%; (b) Load 50%

vessel. The chamber is placed horizontally inside the water tank. Two quartz windows are installed at the chamber to investigate the flame. The flame image is recorded by a video camera. Thermocouples are installed inside the combustion chamber to provide the temperature distribution. The flue gas is sampled at the exit of the boiler to analyze its composition. A control system has been composed to shut off the fuel supply by monitoring the flame and the operation of the boiler.

3. Results and Discussion

Oxy-fuel combustion commonly gives smaller flame with higher intensity compared to the air combustion for all three combustion capacities as shown in Fig. 3. The flame is formed near the burner for the 50 kW case, since the fuel is injected perpendicular to the oxidizer. For the higher capacities of 0.5 and 3 MW, the flame of oxy-fuel combustion is stretched in the streamwise direction. The flame is spread in the radial direction for the air combustion, because the oxidizer is supplied through the swirler.

The temperature distributions inside the combustion chamber (Fig. 4) are consistent with flame images (Fig. 3). The temperature decreases rapidly at the upstream then gradually as it flows downstream for the 50 kW system (Fig. 4(a)). The oxy-fuel yields higher temperature at the upstream for the high combustion load (29 kW), while the difference is not distinct for the low combustion load (12 kW). For the higher capacity of 5 MW (Fig. 4(b)), the high temperature region is formed at the upstream of the combustion chamber, apart from the centerline, when the air is supplied through the outer swirler. The high temperature region is formed along the center line for the oxy-fuel combustion. Although the oxy-fuel combustion should yield smaller flame fullness because of the reduced flow rate, the temperature near the chamber wall ($r/D = 1$) is not lower than that of the air fuel case except the upstream region ($x/D < 1$) due to the gas radiation.

The concentration of CO_2 in the dry flue gas is around 10% for the air combustion and the data are well collapsed for all three systems (Fig. 5). The theoretical concentration of CO_2 for the oxy-fuel combustion is over 95%, but it remains around 90% for the 50 kW system. The discrepancy is proved to be mainly caused by the imperfect sealing of the

system. The sealing is fortified for the systems with higher capacity, which shows higher CO₂ concentration over 95%.

Carbon monoxide (CO) indicates the stability of combustion process. It has not been detected for the 0.5 MW class system for all three combustion modes. The concentration of nitrogen oxide is also regulated as well as CO. Its concentration is around two times higher for the oxy-fuel combustion compared to the conventional air combustion because of the infiltration of the air and high flame temperature (Fig. 6(a)). The NO concentration can be reduced to less than 30 ppm for the oxy-fuel combustion by adopting FGR, since it decreases the flame temperature. Although the oxy-fuel combustion gives higher NO concentration of the exhaust gas, its amount per unit fuel consumption is much smaller due to the reduced flow rate as shown in Fig. 6(b).

4. Conclusions

Oxy-fuel FGR combustion boilers for CO₂ capturing have been developed and their combustion characteristics are investigated. The important conclusions are summarized as below.

1. The oxy-fuel burner can heat the entire combustion chamber of the boiler with the help of gas radiation, so that the oxy-fuel combustion can be applied to the existing boiler system only by retrofitting the burner.

2. The oxy-fuel combustion has been applied to the industrial boiler and gives the concentration of CO₂ in the dry flue gas over 95%.

3. The sealing of the system is found to be critical for the oxy-fuel system to have low NOx emission, and the system in the present study shows significantly reduced NOx

Fig.4 Temperature inside the combustion chamber; (a) along the centerline for the 50 kW class system; (b) for the 0.5 MW class system

Fig.5 Dry based CO₂ concentration of the exhaust gas

emission per unit fuel consumption.

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Fig.6 NO emission for the 0.5 MW class system; (a) dry based concentration; (b) emission per fuel consumption