

# Comparative study on SO<sub>2</sub> release and removal under air and oxy-fuel combustion in a fluidized bed combustor

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**Abstract:** SO<sub>2</sub> release and removal were studied under both the air and oxy-fuel combustion conditions using an anthracite coal from the Jincheng mine in China on a bench-scale fluidized bed combustor (FBC). Special attention was paid to the effects of the combustion atmosphere, O<sub>2</sub> concentration, bed temperature, and limestone addition. The released amount of SO<sub>2</sub> was clearly higher under 30% O<sub>2</sub>/70% CO<sub>2</sub> than that of the air atmosphere. As the O<sub>2</sub> concentration in O<sub>2</sub>/CO<sub>2</sub> mixture increased from 21% to 40%, the released amount of SO<sub>2</sub> increased significantly, but then it decreased when the O<sub>2</sub> concentration increased up to 50%. The bed temperature from 860 to 920 °C has no obvious influence on the SO<sub>2</sub> release but shows a strong influence on the desulfurization with limestone in both oxy-fuel and air conditions. The maximum SO<sub>2</sub> removal efficiency appears to be at 880 to 900 °C for both the air and oxy-fuel combustion conditions.

**Key words:** oxy-fuel combustion; fluidized bed; SO<sub>2</sub> release; limestone desulfuration

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Oxy-fuel combustion is one of the most advanced technologies for carbon capture and storage (CCS). Oxy-fuel circulating fluidized bed (CFB) combustion as one type of oxy-fuel combustion has received special attention due to its wide adaptation in fuels, low NO<sub>x</sub> emissions, and, in particular, in furnace desulphurization. In recent years, a wide range of research involving oxy-fuel CFB has been carried out<sup>[1-5]</sup>. Despite that, research on the release and removal of SO<sub>2</sub> in oxy-fuel CFB is still controversial.

There have been some studies on the difference in SO<sub>2</sub> release between air and oxy-fuel combustion without desulfurization. Tan et al.<sup>[6]</sup> found that even though the concentration of SO<sub>2</sub> in oxy-fuel combustion was higher, its

mass emission was usually slightly lower than that in air combustion. Wang<sup>[7]</sup> drew a similar conclusion and he proposed that the lower SO<sub>2</sub> emission in oxy-fuel combustion was due to the higher capture of fly ash towards sulfur. Duan et al.<sup>[8]</sup> showed that the release of SO<sub>2</sub> in oxy-fuel combustion was significantly higher than that in air combustion when oxygen concentration was higher than 30% in oxy-fuel combustion. The main reason for the result was that the increase in oxygen concentration led to the increase in bed temperature, and subsequently increased the combustion efficiency and sulfur conversion rate. On the other hand, Zheng et al.<sup>[9]</sup> believed that the amount of SO<sub>2</sub> released under both conditions has no obvious difference based on theoretical calculation. Therefore, the difference between SO<sub>2</sub> release in air combustion and oxy-fuel combustion is still uncertain.

In-furnace desulphurization has also been widely studied. The most popular reagent used for desulphurization is limestone. In terms of the mechanisms of limestone desulfurization in the furnace, two types of reaction mechanisms exist in the operational temperature range (i. e., 850 to 950 °C) in oxy-fuel combustion. They are direct sulfation and indirect sulfation reaction. When the temperature is at 850 °C, a high concentration of CO<sub>2</sub> can suppress CaCO<sub>3</sub> decomposition, which leads to a direct sulfation reaction. However, it should be mentioned that with the increase in CO<sub>2</sub> partial pressure, the calcium conversion rate decreases accordingly<sup>[10]</sup>. Jia et al.<sup>[4]</sup> found that desulfurization efficiency was only 40.1%, which was far less than 68.4% for air combustion under similar conditions (i. e. the bed temperature: 850 °C; the Ca/S ratio: 2.5)<sup>[11]</sup>.

In this paper, experiments were conducted on a bench-scale fluidized bed combustor. The effects of combustion atmosphere, oxygen concentration, the bed temperature and limestone addition on the release and removal of SO<sub>2</sub> were investigated.

## 1 Experimental Sections

### 1.1 Fuel, limestone, and bed material

An anthracite coal from the Jincheng mine in China, which is referred to JCA here, was used in the experiment. It was precrushed to granule with particle sizes less than 2.36 mm. The proximate and elemental analysis for the coal are presented in Tab. 1. Prior to the experiments,

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coal samples were exposed to air and dried. Limestone from Shou County in China was used as the sorbent. The particle size for limestone was below 1.18 mm. The chemical compositions of limestone and the resulting ash

of JCA are listed in Tab.2 and Tab.3, respectively. The particle size distributions (PSDs) of the coal and limestone are given in Fig. 1. Quartz sand with a particle size range of 0.18 to 0.55 mm was used as the bed material.

**Tab. 1** Proximate and ultimate analyses of JCA expressed on air-dry basis %

| Proximate analysis |       |      |       | Ultimate analysis |      |      |      |      | LHV/<br>(MJ·kg <sup>-1</sup> ) |
|--------------------|-------|------|-------|-------------------|------|------|------|------|--------------------------------|
| w(M)               | w(A)  | w(V) | w(FC) | w(C)              | w(H) | w(O) | w(N) | w(S) |                                |
| 4                  | 30.24 | 6.72 | 59.04 | 59.35             | 2.56 | 1.29 | 0.72 | 1.84 | 20.48                          |

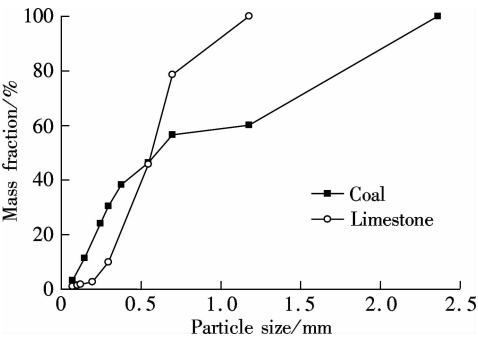
Notes: M is the moisture; A is the ash content; V is the volatile; FC is the fixed carbon; LHV is the lower heating value.

**Tab. 2** Chemical composition of the limestone as sorbent %

| w(CaCO <sub>3</sub> ) | w(MgCO <sub>3</sub> ) | w(Al <sub>2</sub> O <sub>3</sub> ) | w(Fe <sub>2</sub> O <sub>3</sub> ) | w(SiO <sub>2</sub> ) | Others |
|-----------------------|-----------------------|------------------------------------|------------------------------------|----------------------|--------|
| 91.11                 | 3.02                  | 0.73                               | 0.68                               | 2.5                  | 2.38   |

**Tab. 3** Chemical composition of the resulting ash of JCA %

| w(Na <sub>2</sub> O) | w(MgO) | w(Al <sub>2</sub> O <sub>3</sub> ) | w(SiO <sub>2</sub> ) | w(P <sub>2</sub> O <sub>5</sub> ) | w(SO <sub>3</sub> ) | w(K <sub>2</sub> O) | w(CaO) | w(TiO <sub>2</sub> ) | w(Fe <sub>2</sub> O <sub>3</sub> ) |
|----------------------|--------|------------------------------------|----------------------|-----------------------------------|---------------------|---------------------|--------|----------------------|------------------------------------|
| 0.73                 | 0.17   | 36.04                              | 44.23                | 0.23                              | 2.67                | 1.04                | 2.99   | 0.69                 | 5.27                               |



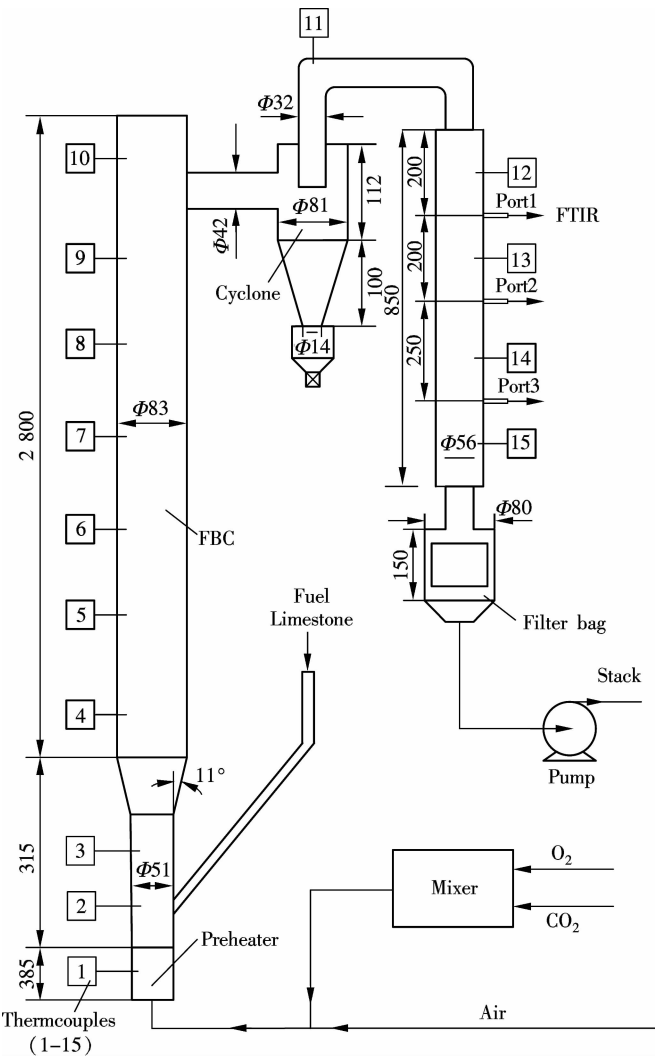
**Fig. 1** The PSDs of JCA and limestone

1.2 Experimental setup

The schematic diagram of the fluidized bed combustor (FBC) experimental set-up is given in Fig. 2. The total height of the combustor is 3 500 mm, including the pre-heating section of 385 mm, the dense section of 315 mm, and the dilute phase section of 2 800 mm. The inner diameters of the dense section and the dilute section are 51 and 83 mm, respectively, and between them there is a transition connection with a slope of 11°. A cyclone is connected to the outlet of the combustor to capture coarse ash followed by a convective section. The length and the inner diameter of the convective section are 850 and 56 mm, respectively. Three sampling ports are arranged to measure flue gas, fly ash, and ash deposits, respectively. Following the convective section, a high temperature filter bag is incorporated to collect the fly ash. The temperature of the combustor is controlled by an electric heater. Coal is fed with a screw feeder at a steady coal-feeding rate of 5 to 20 g/min. Either air or O<sub>2</sub>/CO<sub>2</sub> can be fed into the system separately. A two-gas system makes it easy and simple to switch between air and oxy-fuel combustion.

Before the ignition, quartz sand with the weight of 150 to 200 g is introduced into the combustor. When the temperature of the reactor reaches 800 °C, coal is introduced

into the reactor. Air and oxy-fuel atmosphere can be swit-



**Fig. 2** Schematic diagram of the bench-scale fluidized bed combustor(unit: mm)

ched if necessary before ignition. During ignition, a few coal samples were introduced into the reactor. When the temperature reaches around 850 °C, the amount of coal

can be increased to the setting value.

The difference in the streams of gas flow affected the residence time of the fluidized bed status and particles, consequently affecting the combustion and pollutant emissions. Therefore, it is more reliable to keep the same gas velocity during all the experiments. However, the fact has to be considered that when too much coal is introduced into the furnace, the furnace temperature will become out of control, particularly under the high oxygen concentration in oxy-fuel combustion. Therefore, during the test, the amount of coal and the flow of the gas should be reduced to ensure a stable bed temperature. The running time of each case is about 30 to 60 min.

For comparison among different combustion cases, the concentration of oxygen in the flue gas at the outlet for all conditions is set to be 6%. The concentration of SO<sub>2</sub> is measured on-line by the Fourier transform infrared spectroscopy (FTIR).

### 1.3 Data processing

In order to compare the differences in the release of SO<sub>2</sub> under different combustion conditions, the volume concentration of SO<sub>2</sub> can be converted into the amount of its release by

$$C_m = \frac{V_g^0 \times C_v \times 2.619}{Q_{ar,net}} \quad (1)$$

where  $C_m$  is the amount of SO<sub>2</sub> release without limestone;  $V_g^0$  is the actual amount of theoretical flue gas, m<sup>3</sup>/kg;  $C_v$  is the volume concentration of SO<sub>2</sub>, 10<sup>-6</sup>;  $Q_{ar,net}$  is the lower heating value of the fuel, MJ/kg; 2.619 is the density of SO<sub>2</sub> under the standard conditions, mg/m<sup>3</sup>.

The removal efficiency of SO<sub>2</sub> is calculated by

$$\eta = \frac{C_0 - C_L}{C_0} \times 100\% \quad (2)$$

where  $C_0$  is the amount of SO<sub>2</sub> release without limestone, mg/MJ;  $C_L$  is the amount of SO<sub>2</sub> release with limestone, mg/MJ.

The utility of limestone  $\xi$  as sorbent is calculated by

$$\xi = \frac{\eta_{SO_2}}{n_{Ca}/n_S} \quad (3)$$

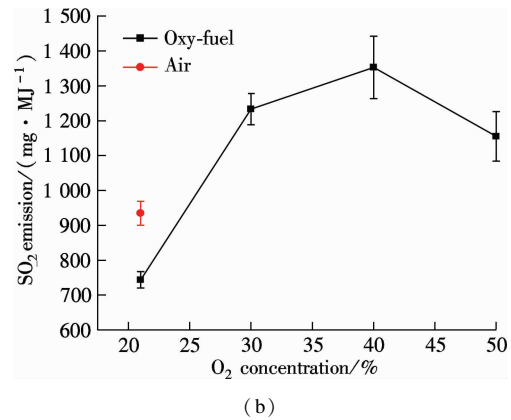
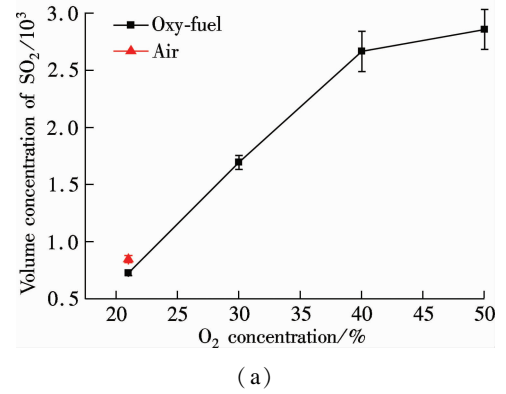
## 2 Results and Discussion

### 2.1 SO<sub>2</sub> release

#### 2.1.1 Effect of O<sub>2</sub> concentration on SO<sub>2</sub> release

SO<sub>2</sub> release is represented by both the volume concentration and mg/MJ as shown in Fig. 3(a) and Fig. 3(b), respectively. It can be noted that in Fig. 3(a), SO<sub>2</sub> concentration increases linearly with the O<sub>2</sub> concentration of 21% to 40% and then increases slowly with the O<sub>2</sub> concentration of 40% to 50%, deviating from the previous

linear curve. The SO<sub>2</sub> concentration under air combustion is slightly higher than that in oxy-fuel combustion at the same O<sub>2</sub> concentration of 21%. In Fig. 3(b), when the SO<sub>2</sub> release is represented in mg/MJ, SO<sub>2</sub> emission increases with the increase in the O<sub>2</sub> concentration from 21% to 40% in oxy-fuel combustion and then SO<sub>2</sub> emission decreases with the O<sub>2</sub> concentration from 40% to 50%. The emission of SO<sub>2</sub> under air combustion is significantly higher than that in oxy-fuel combustion under the same O<sub>2</sub> concentration of 21%.



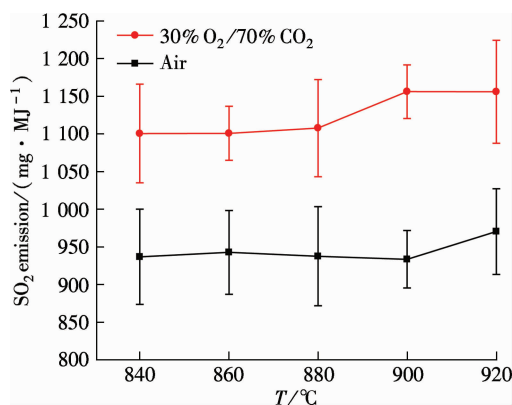
**Fig. 3** Effect of O<sub>2</sub> concentration on SO<sub>2</sub> release. (a) The volume concentration of SO<sub>2</sub>; (b) SO<sub>2</sub> emission

Two reasons can be used to explain why SO<sub>2</sub> emission is so low in oxy-fuel combustion (21% O<sub>2</sub>). The high thermal capacity but low oxygen diffusivity in the CO<sub>2</sub> atmosphere reduces the surface temperature of coke particles and then leads to the decrease of SO<sub>2</sub> release. Meanwhile, the high concentration of CO<sub>2</sub> can inhibit coke combustion and lead to higher CO formation in the furnace to create a reductive atmosphere. Therefore, SO<sub>2</sub> can be reduced to COS by CO<sup>[12]</sup>. The substantial increase of oxygen concentration will increase the surface temperature of the particles and enhance the oxidation rate of coke, which will increase the emission of SO<sub>2</sub>. Meanwhile, the effects of CO formation on the reduction of SO<sub>2</sub> will be weakened<sup>[13-14]</sup>. The combined impacts of the above two reasons lead to the increase in SO<sub>2</sub> emission at concentrations of O<sub>2</sub> from 20% to 40%. The SO<sub>2</sub> emis-

sion begins to decline when the O<sub>2</sub> concentration exceeds 40%. There may be two reasons for this. One is that the volume concentration of SO<sub>2</sub> increases significantly due to the reduction in the total volume flow of flue gas. SO<sub>2</sub> is easily oxidized to SO<sub>3</sub> and subsequently forms H<sub>2</sub>SO<sub>4</sub> by reacting with H<sub>2</sub>O at the low temperature of flue gas below 1 000 °C<sup>[15–16]</sup>. The other reason is that SO<sub>2</sub> may react with alkaline earth metal in fly ash<sup>[8,15]</sup>. Therefore, SO<sub>2</sub> emission in the oxy-fuel combustion depends highly on O<sub>2</sub> concentration.

### 2.1.2 Effect of bed temperature on SO<sub>2</sub> release

The effect of the bed temperature on SO<sub>2</sub> release rate is shown in Fig. 4 under air and 30% O<sub>2</sub>/70% CO<sub>2</sub> combustion. The bed temperature ranges from 840 to 920 °C. It can be found that SO<sub>2</sub> does not show any obvious change except to rise slightly above 900 °C. Generally, SO<sub>2</sub> release is not influenced by the bed temperature regardless whether in air combustion or oxy-fuel combustion below 900 °C. As described in Refs. [17–18], there are three main forms of sulfur in coal, including pyrite, organic sulphur, and sulfates. Pyrite will decompose at around 600 °C, sulfates will decompose over 1 000 °C, and organic sulfur will decompose at different temperatures ranging from 400 to 1 000 °C. Part of organic sulfur can be bonded to the coal matrix and retained in the ash due to the incomplete burnt condition. However, the increased temperature will weaken this retention of sulphur in ash as well as increasing the conversion of char<sup>[8]</sup>.



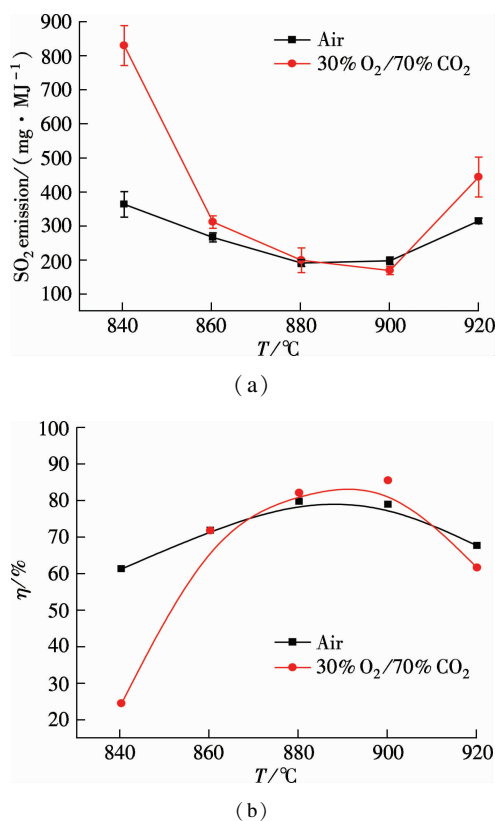
**Fig. 4** Effect of bed temperature on SO<sub>2</sub> release under air and oxy-fuel combustion

## 2.2 SO<sub>2</sub> removal

### 2.2.1 The effect of bed temperature

Fig. 5 shows the SO<sub>2</sub> removal as a function of the bed temperature under both air and oxy-fuel combustion conditions during anthracite combustion with a Ca/S ratio of 2.5. Fig. 5 (a) shows the effect of bed temperature on SO<sub>2</sub> emissions using mass concentration, and Fig. 5 (b) shows the effect of bed temperature on desulfurization efficiency, which are calculated by Eq. (2). It can be seen

from Fig. 5 (a) that the bed temperature has significant effects on SO<sub>2</sub> emissions under both air and oxy-fuel combustion. The SO<sub>2</sub> emissions are similar when the temperature varies from 860 to 900 °C. The SO<sub>2</sub> emission in oxy-fuel combustion is high at 840 and 920 °C. Fig. 5 (b) shows that the desulfurization efficiency increases with the increase in the temperature from 880 to 900 °C and then decreases under both air and oxy-fuel combustion. The desulfurization efficiency in air is higher than that in oxy-fuel combustion at 840 and 920 °C, but a little lower within 870 to 920 °C. According to the thermodynamic equilibrium curve of CaCO<sub>3</sub> calcination<sup>[9]</sup>, for oxy-fuel combustion, the CO<sub>2</sub> concentration can be enriched up to a value as high as 90%. Therefore, the limestone can be surrounded by high CO<sub>2</sub> concentrations ranging from 40% to 90%. Under such high CO<sub>2</sub> concentrations, the sorbent can behave in two ways depending on the temperature. At 840 °C, direct sulphation may be dominant and indirect sulphation may be dominant at temperatures higher than 840 °C. The sulphation conversions achieved under indirect sulphation are normally higher than those achieved under the direct sulphation optimum temperature for sulphur<sup>[19]</sup>. At 840 °C, direct sulphation is dominant for oxy-fuel combustion, and indirect sulphation for air combustion. Therefore, the desulfurization efficiency for air combustion is higher than that for the oxy-fuel combustion. The reaction is gradually transformed into indirect



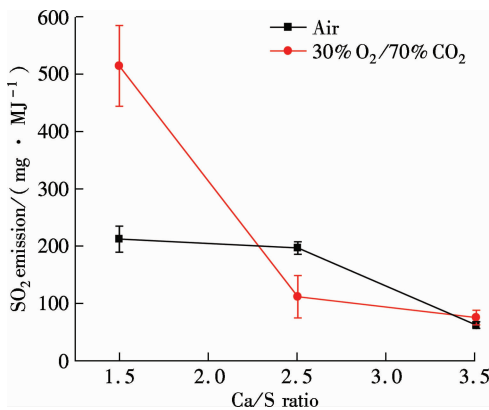
**Fig. 5** Effects of bed temperature on SO<sub>2</sub> removal under air and oxy-fuel combustion with limestone addition. (a) SO<sub>2</sub> emission with limestone addition; (b) Removal efficiency of SO<sub>2</sub>

sulphation as the temperature increases; as a consequence, the maximum desulfurization efficiency can be reached at about 890 °C. The desulfurization efficiency under the oxy-fuel combustion at this temperature is higher than that under air combustion. The possible reason is that, for air combustion, the long-term heating at high temperatures causes the sintering of the calcined CaO.

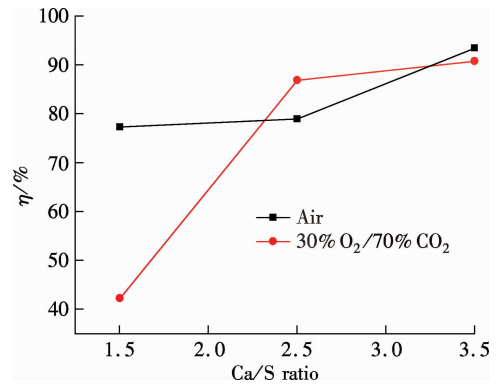
At 920 °C, the desulfurization efficiency under the oxy-fuel combustion is lower than that under air combustion, and it may be caused by the intensive sintering of calcined CaO<sup>[20–21]</sup>. Above all, it is clear that temperature is one of the most important parameters that affect the SO<sub>2</sub> removal process under both air combustion and oxy-fuel combustion. The maximum desulfurization efficiency is shifted to a higher temperature from air combustion to oxy-fuel combustion.

### 2.2.2 The effect of Ca/S ratio

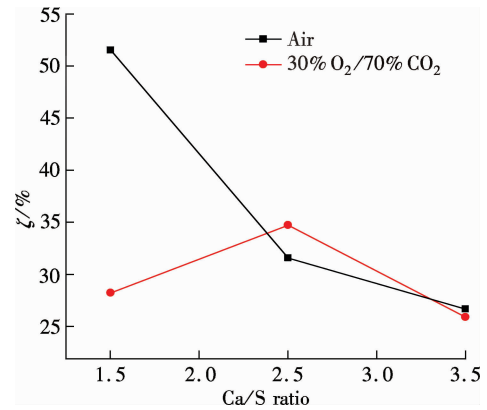
The calcium to sulfur ratio is an important parameter in the limestone desulfurization system of a fluidized bed because it has a significant impact on boiler safety and economy. As given in Fig. 6, the SO<sub>2</sub> removal under the same calcium to sulfur ratio is different under air and oxy-fuel combustion, and the difference is most significant when the calcium to sulfur ratio is 1.5. The SO<sub>2</sub> emission under oxy-fuel is significantly lower than that under the air combustion atmosphere. As shown in Fig. 7, the SO<sub>2</sub> removal efficiency is 51.5% and 77.2%, respectively when the Ca/S ratio is 1.5 under the air and oxy-fuel combustion at 900 °C. When the calcium to sulfur ratios are 2.5 and 3.5, the removal efficiency are closer under both conditions. This agrees with previous findings<sup>[4,8]</sup>. According to Fig. 8, with the increase in the Ca/S ratio, the utilization of calcium has a downward trend. When the Ca/S ratio is 2.5, limestone utilization is the maximum under the oxy-fuel combustion atmosphere. The low calcium to sulfur ratio is preferable under the air combustion atmosphere, while the Ca/S ratio of 2.5 is appropriate for JCA at 900 °C under an oxy-fuel combustion atmosphere.



**Fig. 6** The effect of Ca/S ratio on SO<sub>2</sub> emission at the bed temperature of 900 °C under air and oxy-fuel combustion atmosphere



**Fig. 7** The effect of Ca/S ratio on SO<sub>2</sub> removal efficiency at the bed temperature of 900 °C under air and oxy-fuel combustion atmosphere



**Fig. 8** The effect of Ca/S ratio on limestone utilization at the bed temperature of 900 °C under air and oxy-fuel atmosphere

## 3 Conclusion

For JCA, when the oxygen concentration is between 21% and 40%, increasing the oxygen concentration can significantly increase SO<sub>2</sub> emission. When the oxygen concentration is increased to 50%, SO<sub>2</sub> has a downward trend. Under the air combustion, SO<sub>2</sub> emission is slightly higher than that in oxy-fuel combustion (Here, 21% O<sub>2</sub>/79% CO<sub>2</sub>), and far lower than these under higher O<sub>2</sub> concentrations in oxy-fuel combustion. A bed temperature (860 to 920 °C) has no significant effect on the emission of SO<sub>2</sub>. When the Ca/S ratio is 2.5, the effect of bed temperature on SO<sub>2</sub> removal is the same as that under the air and oxy-fuel combustion atmosphere, but at 840 °C, the removal efficiency under oxy-fuel combustion is much lower than that under air combustion. Under the air combustion atmosphere, with the increase in the Ca/S ratio (1.5 to 3.5), the utilization ratio of limestone decreases. When the Ca/S ratio is 2.5, the limestone utilization ratio is quite high at the bed temperature of 900 °C under the oxy-fuel combustion.

## References

- [1] Kuivalainen R, Pikkariainen T, Leino T, et al. Development of CFB technology to provide flexible air/oxy oper-

- ation for a power plant with CCS[C]//*The 34th International Technical Conference on Coal Utilization & Fuel Systems*. Clearwater, FL, USA, 2009.
- [2] Nsakala N, Liljedahl G N, Turek D G, et al. Oxygen-fired circulating fluidized bed boilers for greenhouse gas emissions control and other applications [C]//*The Second Annual National Conference on Carbon Sequestration*. Alexandria, VA, USA, 2004.
  - [3] Jia L, Tan Y, Anthony E J, et al. Emissions of SO<sub>2</sub> and NO<sub>x</sub> during oxy-fuel CFB combustion tests in a mini-circulating fluidized bed combustion reactor [J]. *Energy & Fuels*, 2009, **24**(2): 910–915.
  - [4] Jia L, Tan Y, Wang C, et al. Experimental study of oxy-fuel combustion and sulfur capture in a mini-CFBC [J]. *Energy & Fuels*, 2007, **21**(6): 3160–3164.
  - [5] Duan L, Zhao C, Zhou W, et al. O<sub>2</sub>/CO<sub>2</sub> coal combustion characteristics in a 50 kWth circulating fluidized bed [J]. *International Journal of Greenhouse Gas Control*, 2011, **5**(4): 770–776.
  - [6] Tan Y, Croiset E, Douglas M A, et al. Combustion characteristics of coal in a mixture of oxygen and recycled flue gas [J]. *Fuel*, 2006, **85**(4): 507–512.
  - [7] Wang L. Experimental and modeling study of SO<sub>2</sub> behavior during oxy combustion in fluidized beds [D]. Salt Lake City, USA: Department of Chemical Engineering of the University of Utah, 2012.
  - [8] Duan L, Zhou W, Li H, et al. Sulfur fate during bituminous coal combustion in an oxy-fired circulating fluidized bed combustor [J]. *Korean Journal of Chemical Engineering*, 2011, **28**(9): 1952–1955.
  - [9] Zheng L, Furimsky E. Assessment of coal combustion in O<sub>2</sub> + CO<sub>2</sub> by equilibrium calculations [J]. *Fuel Processing Technology*, 2003, **81**(1): 23–34.
  - [10] Mao Y, Fang M, Luo Z, et al. Calcination and desulfurization of limestone under O<sub>2</sub>/CO<sub>2</sub> atmosphere [J]. *Journal of Fuel Chemistry and Technology*, 2004, **32**(3): 323–328.
  - [11] Liu H, Katagiri S, Kaneko U, et al. Sulfation behavior of limestone under high CO<sub>2</sub> concentration in O<sub>2</sub>/CO<sub>2</sub> coal combustion [J]. *Fuel*, 2000, **79**(8): 945–953.
  - [12] Dong X, Wang H, Liu H, et al. Study on SO<sub>2</sub> emission under various atmospheres during coal combustion [J]. *Journal of Environmental Sciences*, 2003, **23**(3): 322–326.
  - [13] Du Y, Wang J, Wang X, et al. Analysis of pollutant discharge of coal combustion in oxygen-enriched atmosphere [J]. *Coal Conversion*, 2011, **34**(3): 75–78.
  - [14] Liu H, Qiu J, Xu Z, et al. Release of NO and SO<sub>2</sub> in high-concentration CO<sub>2</sub> atmosphere during coal combustion [J]. *Journal of Engineering Thermophysics*, 2008, **29**(2): 354–356.
  - [15] Fleig D, Normann F, Andersson K, et al. The fate of sulphur during oxy-fuel combustion of lignite [J]. *Energy Procedia*, 2009, **1**(1): 383–390.
  - [16] Ahn J, Okerlund R, Fry A, et al. Sulfur trioxide formation during oxy-coal combustion [J]. *International Journal of Greenhouse Gas Control*, 2011, **5**(S1): 127–135.
  - [17] Anthony E J, Granatstein D L. Sulfation phenomena in fluidized bed combustion systems [J]. *Progress in Energy and Combustion Science*, 2001, **27**(2): 215–236.
  - [18] Miura K, Mae K, Shimada M, et al. Analysis of formation rates of sulfur-containing gases during the pyrolysis of various coals [J]. *Energy & Fuels*, 2001, **15**(3): 629–636.
  - [19] de Diego L F, Rufas A, García-Labiano F, et al. Optimum temperature for sulphur retention in fluidized beds working under oxy-fuel combustion conditions [J]. *Fuel*, 2013, **114**: 106–113.
  - [20] Chen C, Zhao C, Liang C, et al. Calcination and sintering characteristics of limestone under O<sub>2</sub>/CO<sub>2</sub> combustion atmosphere [J]. *Fuel Processing Technology*, 2007, **88**(2): 171–178.
  - [21] Borgwardt R. Calcium oxide sintering in atmospheres containing water and carbon dioxide [J]. *Industrial & Engineering Chemistry Research*, 1989, **28**(4): 493–500.

## 流化床空气和富氧燃烧气氛下 SO<sub>2</sub> 的释放和脱除特性比较研究

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**摘要:**在一个小型流化床试验台上比较了晋城无烟煤在空气和富氧燃烧下 SO<sub>2</sub> 的释放和脱除特性,考察了燃烧气氛、氧浓度、床温和石灰石的添加等因素的影响。研究结果表明:在 30% O<sub>2</sub> 的富氧燃烧条件下 SO<sub>2</sub> 的释放量明显高于其在空气燃烧条件下的释放量;随着富氧燃烧气氛中 O<sub>2</sub> 浓度的增加(从 21% 增至 40%),SO<sub>2</sub> 的释放量显著增加,当氧浓度达到 50% 时,SO<sub>2</sub> 的释放量有下降的趋势。床温 860~920 °C 对 SO<sub>2</sub> 的释放没有明显的影响,但对其脱除有显著的影响。在空气和 30% O<sub>2</sub> 富氧气氛下,SO<sub>2</sub> 的最佳脱硫温度均为 880~900 °C。

**关键词:**富氧燃烧;流化床;SO<sub>2</sub> 释放;石灰石脱硫

**中图分类号:**TK224.1