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Co-combustion of municipal solid waste and coal gangue in a circulating fluidized bed combustor

Jianguang Qin[1] · Ruidong Zhao[1] · Tianju Chen[1] · Zhongyue Zi[1] · Jinhu Wu[1]

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Abstract Mixed incineration of municipal solid waste (MSW) in existing coal gangue power plant is a potentially high-efficiency and low-cost MSW disposal way. In this paper, the co-combustion and pollutants emission characteristic of MSW and coal gangue was investigated in a circulating fluidized bed (CFB) combustor. The effect of MSW blend ratio, bed temperature and excess air ratio was detailedly studied. The results show the NO_x and HCl emission increases with the increasing MSW blend ratio and the SO_2 emission decreases. With the increase of bed temperature, the CO emission decreases while the NO_x and SO_2 emission increases. The HCl emission is nearly stable in the temperature range of 850–950 °C. The increase of excess air ratio gradually increases the NO_x emission but has no significant effect on the SO_2 emission. The HCl emission firstly increases and then decreases with the increase of excess air ratio. For a typical CFB operating condition with excess air ratio of 1.4, bed temperature of 900 °C and MSW blend ratio of 10%, the original CO, NO_x, SO_2 and HCl emissions are 52, 181, 3373 and 58 mg/N m^3 respectively.

Keywords Municipal solid waste · Coal gangue · Co-combustion · Circulating fluidized bed

1 Introduction

From 2006 to 2016, the amount of municipal solid waste (MSW) in China increases from 148 to 204 million tons (National Bureau of Statistics of China 2017). MSW disposal has become one of the most serious issues in China. Due to the advantages of volume reduction, energy recycling and hygienic control, MSW incineration has faster development than other disposal methods (Cheng and Hu 2010). However, the construction of MSW incineration power plant is facing great resistance because of its high investment cost and secondary pollutions, low efficiency and public protest. In comparison with establishing a new MSW incineration power station, co-combustion of MSW and coal gangue in existing power generation station has greater potential (Leckner 2007). Coal gangue is one of the largest industrial solid wastes and has low calorific value and volatile content (Liu and Liu 2010). Circulating fluidized bed (CFB) is generally used for its combustion and high-quality coal is also added to keep stable burning. MSW has high volatile content and low ignition temperature, so the co-combustion of coal gangue and MSW instead of coal can not only realize the efficient and clean disposal of MSW but also improve the combustion characteristics of coal gangue. More important, by the co-combustion of coal gangue and MSW, no new MSW incineration power station is needed which will dramatically reduce the capital investment and public resistance.

The co-combustion of coal with biomass (Akram et al. 2015; Kumar and Singh 2016; Luo and Zhou 2017) and sludge (Areeprasert et al. 2016; Kumar and Singh 2017) have been widely studied and the results verify the feasibility of co-combustion. Due to the demand of MSW disposal, the co-combustion of coal and MSW has also attracted more attention in recent years. Muthuraman et al.

✉ Ruidong Zhao
zhaord@qibebt.ac.cn

[1] Key Laboratory of Biofuel, Qingdao Institute of Bioenergy and Bioprocess Technology, Chinese Academy of Sciences, Qingdao 266101, China

(2010a) found the ignition and carbon burnout of MSW with high ash Indian coal is even better than the Indonesian coal/Indian coal blend which indicated the feasibility for replacing Indonesian coal with MSW. Lu et al. (2016) studied the co-combustion of MSW and coal by use of numerical simulation and bubbling fluidized bed (BFB). The results show that the MSW blend ratio can be increased to 30% without major modification of the coal-fired BFB reactor and the minimum CO emission was found at the mixing proportion of 20%. The mixing of MSW helped to decrease the SO_2 and NO emission. Suksankraisorn et al. (2004) investigated the co-combustion of MSW and high sulfur Thai lignite in a BFB and found the addition of MSW will lower the bed temperature and carbon combustion efficiency. The emission of SO_2 can be reduced by up to 7%–18% as a result of fuel sulfur dilution while the NO emission slightly increases with the increase of MSW fraction. Besides of the common pollutants, it is found that the co-combustion of MSW and coal can reduce the yield and toxicity of PAHs (Polycyclic Aromatic Hydrocarbons) and PCDD/Fs (Polychlorinated dibenzo-*p*-dioxins and dibenzofurans) (Peng et al. 2016; Yan et al. 2006). The raw MSW has complicated components and various sizes which are difficult to directly combust in existing CFB. So refuse-derived Fuel (RDF) is also used instead of the raw MSW in the co-combustion and the results show the pollutants can be suppressed by the additives (such as CaO) in the RDF preparation process (Chyang et al. 2010; Rigamonti et al. 2012; Wei et al. 2009). Besides, because of the high moisture content in MSW, hydrothermal treatment is found to be useful to improve the co-combustion of coal and MSW (Jin et al. 2013; Muthuraman et al. 2010b). Owing to the poor characteristic of coal gangue, the co-combustion of coal gangue with coal or biomass also has been studied and the results show the co-combustion can lower the ignition and burnout temperature which is beneficial to the combustion of coal gangue (Zhang et al. 2015; Zhou et al. 2015).

However, there are fewer studies on the co-combustion of coal gangue and MSW which is meaningful for the synergistic utilization of solid wastes. The great differences between the coal gangue and MSW may influence the combustion behavior of the blends. Therefore, the purpose of this study is to investigate the combustion and pollutants emission characteristic of MSW and coal gangue in a circulating fluidized bed combustor. The effect of MSW blend ratio, bed temperature and excess air ratio are described in detail.

2 Experimental

2.1 Apparatus

The experimental apparatus consists of a circulating fluidized bed combustor, a fuel feeding system, a flue gas cooler and a gravity dust filter. The schematic diagram of the experimental apparatus is shown in Fig. 1. The thermal capacity of the CFB is about 100 kWth. The combustor is composed of a furnace, a cyclone, a dipleg and loop seal. The furnace has an inside diameter of 108 mm and a height of 6 m. Four electrical heaters each with the heating power of 2 kW are furnished along the furnace in order to raise the furnace temperature at the beginning of experiments. The inside diameter of the dipleg is 70 mm. The fluidizing air is preheated by an air preheater and then flows into the furnace through the air distributor plate. The fuel feeding system consists of two hoppers and a screw feeder. Coal gangue and MSW are added into the hoppers after well mixed and then fed into the furnace by the screw feeder. The ash is discharged from the bottom of the furnace.

Temperature is measured by thermocouples located at heights of 150, 840, 2550, 4170, and 5850 mm above the

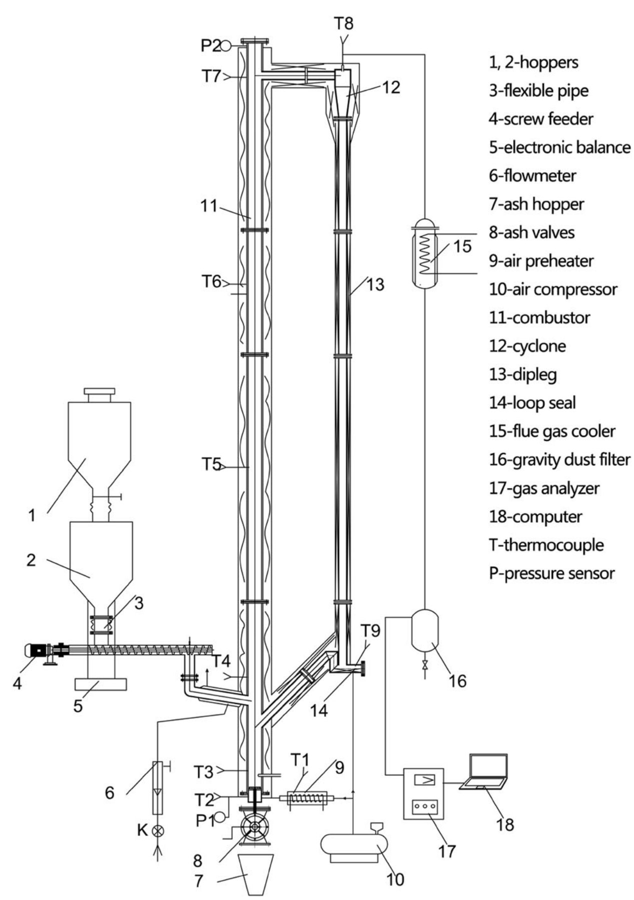

Fig. 1 Schematic diagram of the experimental apparatus

air distributor plate and also at the air chamber, cyclone and loop seal. Pressure is measured at 100, 940, 2450, 4070, and 5750 mm above the air distributor plate. The concentrations of O_2, CO_2, CO, SO_2, NO_x and HCl in the flue gas are continuously monitored online by a Madur Photon gas analyzer after the gravity dust filter.

2.2 Fuel

The coal gangue was provided by Pingshuo Gangue Power Generation Co., Ltd (Shuozhou City, Shanxi Province, China). It was sieved to particle sizes between 0.3 and 4 mm. Because the composition of real MSW is complex and varied, in order to maintain the consistency of fuel properties, MSW used in present study was simulated by use of pure components (such as wood, polyethylene, rice and so on) according to the composition of real MSW in Shuozhou City (Zhao et al. 2012). These pure components are mixed evenly and then crushed into 0.5–2 mm. The proximate and ultimate analysis of the coal gangue and MSW are shown in Table 1. In the experiments, the coal gangue and MSW were directly mixed according to the MSW blend ratio (the mass fraction of MSW in the mixed fuel) and fed into the circulating fluidized bed combustor together.

2.3 Conditions

The effect of bed temperature, MSW blend ratio, and excess air ratio is investigated. The base experimental conditions for these factors are 900 °C, 10 wt% and 1.3 respectively. When one of the factors is investigated, the rest remains unchanged. The variation range of bed temperature is from 780 to 950 °C. The MSW blend ratio is from 0 to 30 wt% and the excess air ratio is from 1.2 to 1.8. The excess air ratio is determined by $\alpha = 21/(21\text{-}\beta)$. In this equation, α is the excess air ratio and β is the O_2 volume concentration in the flue gas. In order to maintain the steady combustion of the mixture, the feed rate of the mixed fuel is variable according to the bed temperature. Correspondingly, the air flow rate is also changed with the feed rate to realize the specified excess air ratio. The air flow rate used in the experiments is from 40 to 65 m^3/h depending on the experimental conditions.

In experiments, temperature, pressure and pollutants measurements are recorded when the system reaches steady condition (no less than 1 h). The bed temperature is the arithmetic mean value of five thermocouples in the furnace. The measurement results of the gas analyzer are converted based on 6 vol% O_2 in flue gas and expressed in mg/N m^3 (dry basis) at normal state (273 K and 101 kPa).

3 Results and discussion

3.1 Bed temperature

Figure 2 shows the changes of CO/CO_2 emission and the ash carbon content as a function of bed temperature. Obviously, the CO emission and ash carbon content gradually decrease as the bed temperature rises. It means that higher bed temperature is beneficial for the complete combustion of carbon. As a result, the CO_2 emission slightly increases with the increase of bed temperature.

The emission of NO_x and SO_2 varying with bed temperature is shown in Fig. 3. With the increase of bed temperature, the NO_x emission increases correspondingly. When the bed temperature is 950 °C, the NO_x concentration reaches 215 mg/N m^3. It is mainly because the higher temperature will strengthen the oxidization of fuel nitrogen to NO_x (Hill and Smoot 2000; Wang et al. 2012). Besides, the decrease of CO and char weakens the reduction reaction of generated NO_x.

The SO_2 concentration decreases slightly at lower temperature and then greatly increases when the bed temperature exceeds 830 °C. The SO_2 concentration is 3696 mg/N m^3 at the bed temperature of 950 °C. It is mainly because, at low temperature, the self-desulphurization efficiency by the alkali metal in the fuel is higher than the sulphur release with the increase of temperature. On the contrary, at the higher bed temperature, the sulphur retention rate will decrease because of the decomposition of sulphate while the sulphur release rate increases. As a result, the SO_2 concentration firstly decreases and then begins to greatly increase (Lith et al. 2006; Knudsen et al. 2005).

The effect of bed temperature on the HCl emission is given in Fig. 4. The HCl concentration gradually increases

Table 1 Proximate and ultimate analysis of coal gangue and MSW (received basis)

Item	Proximate analysis (%)				Ultimate analysis (%)					
	FC	V	M	A	C	H	O	N	S	Cl
Coal gangue	23.33	22.90	1.52	52.25	28.29	2.24	13.28	0.42	1.99	0.01
MSW	8.18	69.64	8.34	13.80	39.15	5.93	30.38	0.93	0.96	1.01

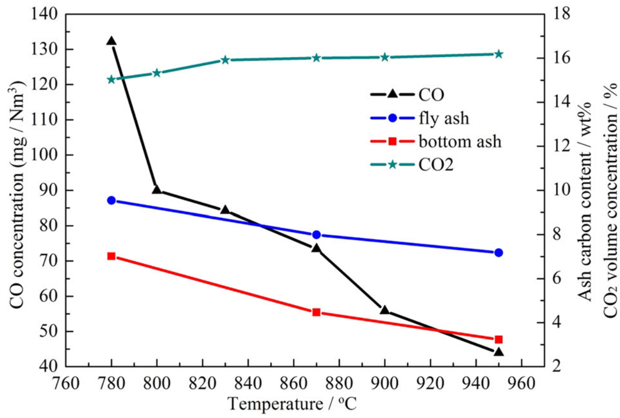

Fig. 2 Effect of bed temperature on the CO/CO_2 emission and carbon content in the ash

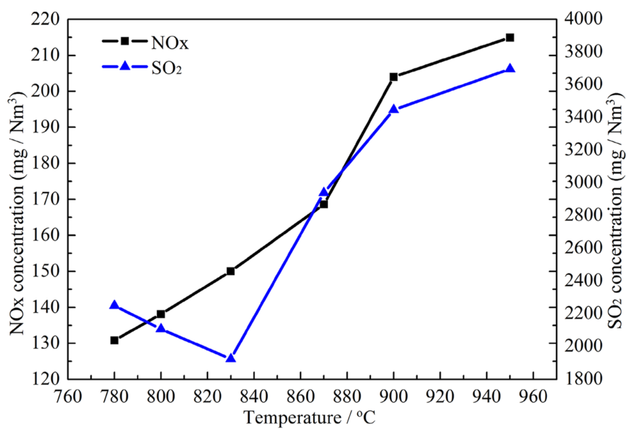

Fig. 3 Effect of bed temperature on the NO_x and SO_2 emissions

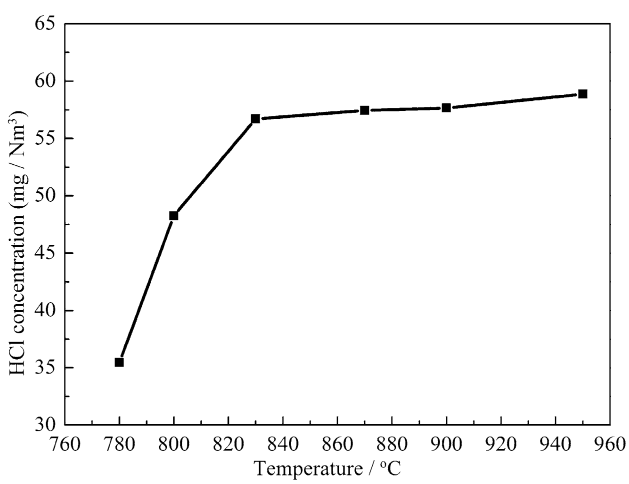

Fig. 4 Effect of bed temperature on the HCl emission

from 35 to 57 mg/N m^3 when the bed temperature is up to 830 °C. With further increase of temperature, the HCl concentration tends to be stable. In general, the operating temperature of CFB is about 850–950 °C, which means the

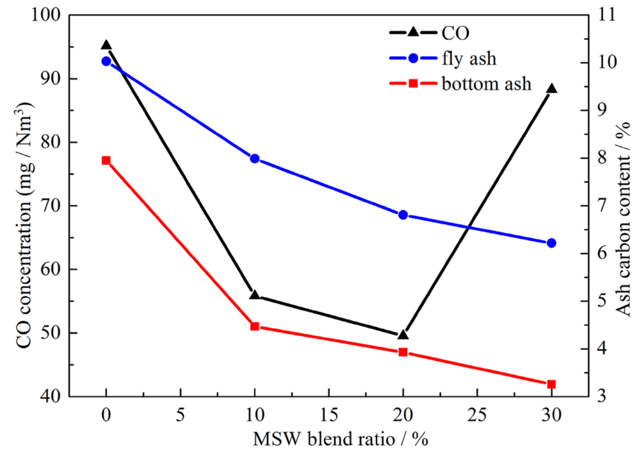

Fig. 5 Effect of MSW blend ratio on the CO emission and carbon content in the ash

HCl emission varies little with the bed temperature for actual CFB.

3.2 MSW blend ratio

Figure 5 shows the variation of CO emission and ash carbon content at different MSW blend ratios. With the addition of MSW, the CO concentration firstly decreases. The minimum CO emission is 50 mg/N m^3 when the MSW blend ratio is 20%. And then the CO emission begins to increase. MSW has higher volatile matter content which can improve the ignition and combustion characteristic of coal gangue. So the CO emission will decrease at the beginning. However, with the further addition of MSW, a large number of volatile matters will be simultaneously released in the combustion and the O_2 in the dilute zone of the furnace will be not sufficient. Therefore, the combustion of volatile matter is incomplete and the CO emission increases accordingly. The carbon content decreases with the increasing MSW blend ratio which means the addition of MSW can improve the combustion of fixed carbon.

The effect of MSW blend ratio on NO_x and SO_2 is shown in Fig. 6. It can be seen that with the increase of MSW blend ratio, NO_x emission rises from 165 to 180 mg/N m^3 while the emission of SO_2 gradually decreases from 3585 to 3086 mg/N m^3. The HCl emission varying with MSW blend ratio is shown in Fig. 7. The HCl concentration linearly increases from 6 to 142 mg/N m^3 with the addition of MSW.

With the addition of MSW, the nitrogen, sulfur and chlorine content in the fuel are changed. So the pollutants emission depends not only on the element conversion but also on the element content. The conversion rate of different elements at different MSW blend ratio is shown in Table 2. The N, S and Cl conversion rate is defined as the

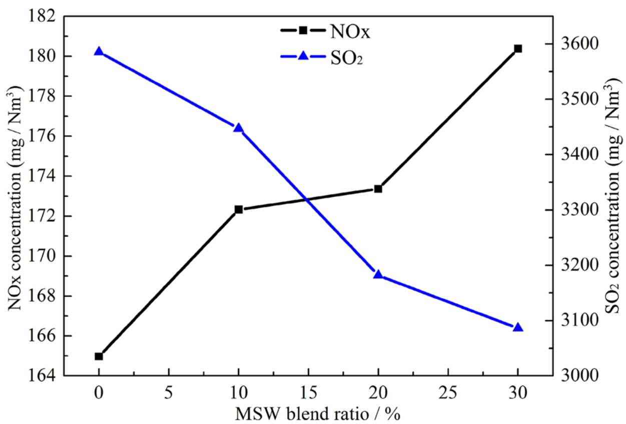

Fig. 6 Effect of MSW blend ratio on the NO_x and SO_2 emissions

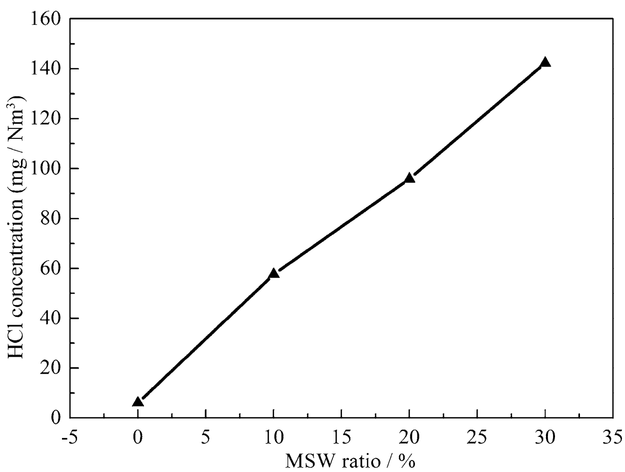

Fig. 7 Effect of MSW blend ratio on the HCl emission

Table 2 Conversion rate of nitrogen, sulfur and chlorine at different MSW blend ratio

MSW blend ratio (%)	N conversion (%)	S conversion (%)	Cl conversion (%)
0	6.8	34.7	22.9
10	6.7	37.2	21.0
20	6.4	38.3	19.3
30	6.4	41.4	20.4

ratio between the element content in the flue gas (contained in the NO_x, SO_2 and HCl respectively) and the corresponding element content in the fuel. From Table 2, it can be seen with the increase of MSW blend ratio, the nitrogen conversion rate slightly decreases which is opposite to the NO_x emission. It is mainly because the nitrogen content of MSW is higher than coal gangue. More nitrogen will be released and subsequently convert to NO_x even if the conversion rate is low. Besides, the decrease of char impairs the NO_x reduction reaction. The sulphur conversion rate gradually increases with the addition of MSW. This is also opposite to the SO_2 emission because the coal gangue used in present study has higher sulphur content than the MSW. The HCl emission obviously increases with the addition of MSW because of the extremely high chlorine content in the MSW even though the chlorine conversion rate has no obvious change. Form the changes of nitrogen, sulphur and chorine, it can be obtained that the pollutants emission is mainly determined by the corresponding elements content in the fuel. In other words, synergistic effect between coal gangue and MSW in the co-combustion is weak compared with the effect of elements content.

3.3 Excess air ratio

The effect of excess air ratio on the CO emission is shown in Fig. 8. The CO emission drops from 87 to 57 mg/N m^3 as excess air ratio increases from 1.2 to 1.4. However, further increase of excess air ratio causes CO emission to slightly increase. This is because the velocity in the combustor rises with the increasing excess air ratio and CO cannot have enough residence time to be complete combustion.

Figure 9 shows the emission of NO_x and SO_2 varying with excess air ratio. The NO_x emission gradually increases from 157 to 281 mg/N m^3 with increasing excess air ratio. It is mainly because the increased O_2 concentration will enhance the oxidizing conversion of fuel N to NO_x. Besides, the decrease of CO can impair the reduction reaction of generated NO_x.

It can be also obtained from Fig. 9 that the SO_2 emission tends to be stable with the increase of excess air ratio. The whole change of SO_2 emission is less than 3.5% which can be said that excess air ratio has no obvious effect on SO_2 emission. Although the reducing atmosphere in the local area of the combustor may suppress the oxidization of sulphur and promote the generation of H_2S, the sulphur and generated H_2S will still be oxidized to SO_2 if the total O_2 is enough in the combustor. Hence, the amount of SO_2 emission is slightly affected.

The change of HCl emission with excess air ratio is shown in Fig. 10. With the increase of excess air ratio, the HCl emission slightly rises from 56 to 58 mg/N m^3 at the beginning and then it gradually drops to 50 mg/N m^3. The increase of excess air ratio air can promote the sufficient combustion and emission of chlorine in the fuel. But too much air will also strengthen the oxidization reaction between the generated HCl and O_2 (shows in Eq. 1) which

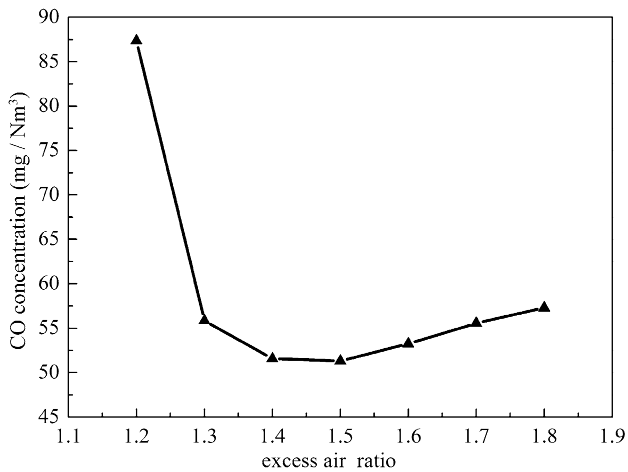

Fig. 8 Effect of excess air ratio on the CO emission

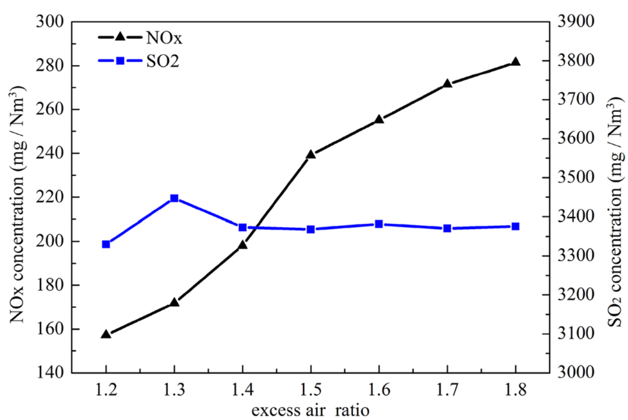

Fig. 9 Effect of excess air ratio on the NO and SO_2 emissions

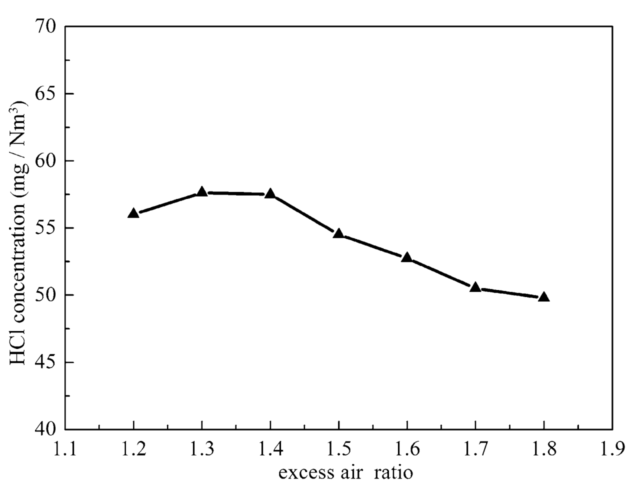

Fig. 10 Effect of excess air ratio on the HCl emission

results in the consequent decease of HCl emission (Gullett et al. 1998).

$$HCl + O_2 \rightarrow Cl_2 + H_2O. \quad (1)$$

4 Conclusions

Co-combustion of MSW and coal gangue in existing CFB coal gangue power station was proposed as one of the most efficient MSW disposal method. The effect of bed temperature, MSW blend ratio and excess air ratio on the co-combustion characteristic of MSW and coal gangue was investigated in a circulating fluidized bed combustor. The results can be summarized as follows:

(1) The increase of bed temperature is beneficial to complete combustion but will significantly increase the emission of NO_x and SO_2. The HCl emission varies little with the bed temperature in the actual CFB operating temperature range (850–950 °C).

(2) The appropriate addition of MSW can improve the combustion efficiency and the minimum CO emission of 50 mg/N m^3 is reached when the MSW blend ratio is 20%. With the increase of MSW blend ratio, the NO_x and HCl emission increases while SO_2 emission decreases due to the corresponding elements content in the mixed fuel.

(3) The optimum excess air ratio for the CO emission is 1.4. The increase of excess air ratio increases the NO_x emission but has no significant effect on the SO_2 emission. The HCl emission firstly increases and then gradually decreases with the increase of excess air ratio.

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