Characterization of Municipal Solid Waste Incineration and Flue Gas Emission Under Anoxic Environment in Tibet Plateau

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Characterization of Municipal Solid Waste Incineration and Flue Gas Emission under Anoxic Environment in Tibet Plateau

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Highlights

• The organic matter, inorganic matter, recyclable and moisture content of garbage in Lhasa are 28.63%, 13.04%, 58.22% and 33.8%, respectively.

• low calorific value of MSW in Lhasa city is 5994kj/kg in rainy season and 7877kj/kg in dry season, with an average of 6935.5kj/kg.

• The concentrations of SO_2, CO, HCI, dust and NOx in the flue gas discharged under the ordinary condition of low anoxic condition are 49.79mg/m^3, 5.34mg/m^3, 48.22mg/m^3, 2.67mg/m^3 and 301.78mg/m^3 respectively.

• The optimal incineration conditions with low pollutant emission were at temperature 900℃, oxygen content in the range of 6% ~ 8% and micro- negative pressure close to 0Pa.

• The contents of Ca in slag and fly ash are the highest, and the contents of Zn, Cu, Pb and Ba in slag and fly ash are higher.

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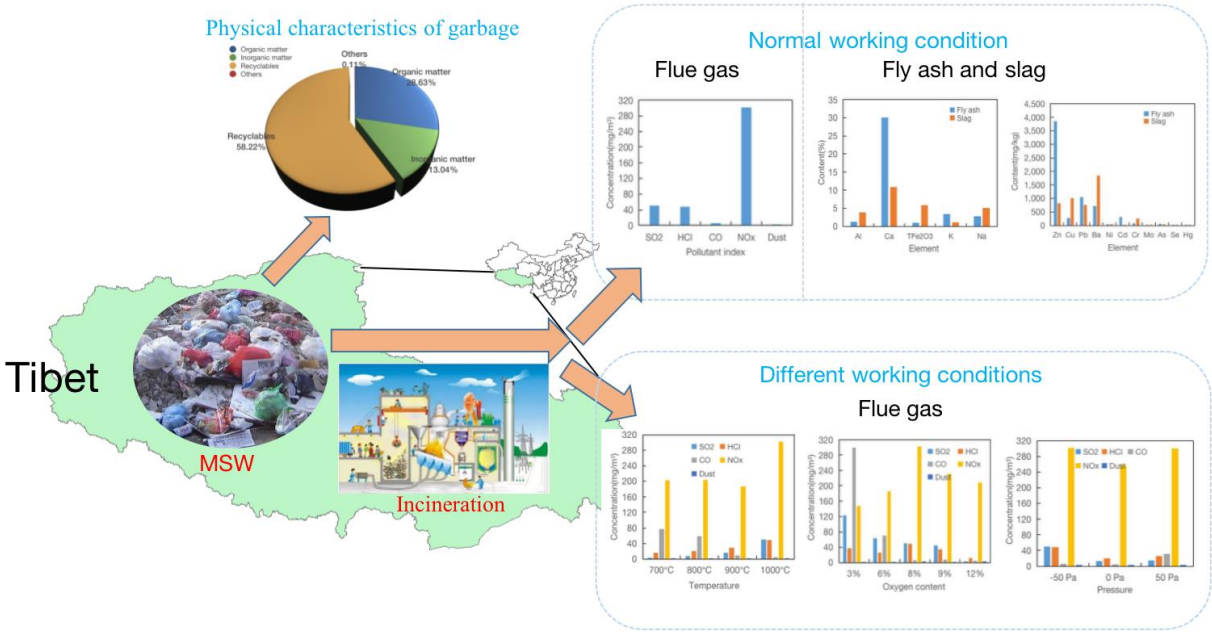
Graphical Abstract



Abstract: Waste incineration is a process of full combustion reaction between waste and oxygen at high temperature. It is a new problem whether the special natural environmental conditions of Tibet Plateau, such as low air pressure, low oxygen content and low temperature, will affect the waste incineration in the plateau area. In this work, the influence of different parameters on MSW incineration efficiency and flue gas emission were investigated. The results showed that the temperatures exhibited a significant impact on the flue gas emission. Under the lower temperature, CO was determined to be the main pollutant. With the increase of temperature, NOx became the main pollutant. The optimal temperature range of flue gas emission was between 800ºC to 900ºC. A slight negative pressure in incinerator was benefit for incineration system safety and flue gas emissions. The optimal range was -50Pa to 0Pa. Lower oxygen content (3%-6%) in the incinerator affected the incineration efficiency and flue gas emission. Meanwhile, the high oxygen content had no obvious impact on the flue gas emission, but the cost increased and the service life of the incinerator was affected. The optimal oxygen content in the incinerator was controlled at 6%-8%. Furthermore, the air temperatures, pressures and oxygen content in the natural environment had no significant effect on MSW incineration process. Increasing the air volume would bring about the increase of N_2 in the incinerator. This work provides the basic data support for MSW incineration technology in plateau area.

Keywords: Municipal solid waste; Incineration; Flue gas emission characterization; Anoxic environment; Tibet plateau

1. Introduction

As a plateau city, the discharge amount of the municipal solid waste (MSW) in Tibet has constantly been on the rise. The output and treatment rate of Tibet's urban domestic waste are shown in Table S1. The average annual growth rate of urban domestic waste in Tibet will reach 20% from 2014 to 2018. And city of Lhasa as an important tourist destination, tourism waste generated in the peak season has gradually increased in recent years (Zhou et al.,2019). At present, sanitary landfill being the main disposal method of MSW in Tibet, it inevitably produces secondary pollution such as leachate and landfill gas that affect the surrounding environment, an environment in which it is difficult to relocate the landfill site (Fang et al., 2012). Incineration technology has become the development trend of MSW treatment technology in domestic and foreign countries due to its rapid treatment, obvious capacity reduction and complete harmless treatment as well as recycle energy (Hartenstein et al., 1996). As shown in Fig.S1(in Table S2), the proportion of incineration in MSW disposal in China has increased gradually in recent years. Secondary pollution would be caused by high moisture content, low calorific value and incomplete incineration of raw MSW (Xiao et al., 2007). These pollutants mainly include smoke and dust, acid gases (HCl, SOx, NOx, HF, etc.), heavy metals, organic toxic pollutants, etc. (Labib et al., 2005). Domestic scholars have conducted research on pollutant emission characteristics, which showed that the generation of air pollutants in the incineration process was directly related to the incineration temperature and operation stability (Zhou et al., 2014; Park et al., 2011; Lin et al., 2015). The concentration of acid gas in flue gas increased with the increase of bed temperature (Zang, 2013). NO concentration and peak value also increased with the increase of combustion temperature (Jin et al., 2007; Jin et al., 2010). When the air excess coefficient increased, the NO emission concentration will also increase (Zang, 2013). Some studies have shown that the concentration of NOx increases with the increase of oxygen concentration. However, under the condition of rich oxygen, full combustion can inhibit the formation of NOx (Binlin et al., 2007; Marsh et al., 2007). In addition, the size of MSW also affects the concentration of NOx emission. The concentration of NOx produced by small size MSW was higher than those produced by large size MSW (Guo, 2011). It also shows that the emission concentration of NOx is related to the change of waste characteristics, incinerator outlet temperature, excess air coefficient, oxygen concentration and heating speed as well. (Wheeler et al., 1995).The SO_2 emission concentration increased with the increase of air excess coefficient, while the SO_2 concentration decreased and the NOx concentration increased with the increase of Ca/S ratio (Zang, 2013). The concentration of HCl decreased with the increase of air excess coefficient and Ca/S ratio (Zang, 2013). And the CO concentration and peak value decreased first and then increased with the increase of temperature (Xing et al., 2017).To sum up, MSW incineration was a mature technology at home and abroad, and there were many reports about it. It was also a technology with great development potential.

Due to the many advantages of incineration technology, it has been incorporated into the government's MSW disposal plan of Tibet Autonomous region. The first MSW incineration power plant in Tibet has been built and located in Lhasa, the capital city of Tibet Autonomous Region. It has aroused great concerns from the government and societies. But MSW incineration, as a combustible component of waste, has a violent oxidation reaction with oxygen in the air, the oxygen content in the air plays a decisive role in the whole combustion reaction process. In Tibet, however, at an average altitude of 4000m, the atmospheric pressure was 62KPa, fell by 38% compared with the plain regions, and the oxygen content was only 62% of the plain regions. Under such high altitude anoxic environment, the full combustion of MSW, the characterization of flue gas and its purification has been a problem awaiting answers in the fundamental science and practical engineering application field.

This research on the characteristics of MSW incineration and flue gas emission in Tibet will be a basis for the evaluation of the feasibility of MSW incineration technology in the plateau area, and also the premise of putting forward targeted measures.

In this work, the emission characteristics of flue gas pollutants (SO_2, HCl, CO, NO_X, CO_2, dust) produced by MSW incineration plant of Lhasa were investigated. Meanwhile, the influences of different reaction conditions were studied, such as the temperature, pressure and oxygen content in the anoxic environment of Tibet Plateau.

2. Materials and Methods

2.1 Municipal solid waste characteristics

The physical characteristics of MSW from Lhasa MSW incineration power plant were analyzed, the results were shown in Table1. Experiments for analyzing the physical characteristics of waste were mainly conducted in rainy season. It can be seen from the table that organic matter accounts for 28.63%, inorganic matter accounts for 13.04%, and recyclable accounts for 58.22%. Accounting for 33.8%, the water content is relatively low,. If the data of paper, plastic, textile, glass, metal and bamboo in the table are used as the proportion of recyclable materials, the proportion of recyclables in cities in plain areas such as Beijing, Shanghai, Hangzhou, Chengdu, Guangzhou and Lanzhou is 29.9%, 38.58%, 20.4%, 32.1%, 40.4% and 25.66%, respectively. Based on the investigation of Lhasa City, it is found that there are few scavengers in the city, which makes the recyclable waste account for a high proportion. In addition, there are various heating methods on the plateau, most of which are coal, firewood and cow dung as well, leading to the relatively high inorganic content in the waste. Furtheremore, in the special environment of plateau area, the consumption of fruits and vegetables is not as much as the ones in plain area, therefore the proportion of organic matter is relatively low. It shows that the waste in plateau area has the characteristics of high inorganic matter and recyclable matter, and low

104 organic matter. It can also be seen from the table that the moisture content of municipal solid waste in Lhasa is 33.8%,
105 which is significantly lower than that in other regions of China, and which is conducive to waste incineration. The low
106 water content may be due to the dry climate, low precipitation and small vegetation coverage. The low calorific value is
107 5994kJ/kg in rainy season and 7877kJ/kg (Dan and Han, 2012) in dry season. The average low calorific value of Lhasa
108 municipal solid waste is 6935.5kj/kg, which is higher than the average low calorific value of 5000kJ/kg stipulated in the
109 technical policy of municipal solid waste treatment and pollution prevention. For incineration technology, low/water
110 content and higher low calorific value were the most obvious advantages of Lhasa MSW.

111 Table 1 Physical characteristics of waste

Characteristics	Experimental site	Other Cities					
	Lhasa incineration plant	Lhasa	Beijing	Shanghai	Hangzhou	Chengdu	Guangzhou	Lanzhou
Bulk density (kg/m^3)	389	300	120-240	——	——	——	——	360-420
Water content (wt.%)	33.8	24.39	63.3	59.28	56.5	57.3	55.6	44.26
Organic matter (wt.%)	28.63	20.45	66.2	61.1	64.5	65.7	53.4	36.38
Ash and residue (wt.%)	13.04	22.83	3.9	0.02	15.1	2.1	6.2	37.81
Paper (wt.%)	22.33	23.74	10.9	12.07	6.7	13	8.3	9.7
Plastics (wt.%)	21.95	14.84	13.1	16.57	10.1	12	18.6	11.34
Textiles (wt.%)	5.35	4.5	1.2	2.57	1.2	2.5	10	2.1
Glass (wt.%)	3.9	4.73	1	2.31	2	0.8	1.4	0.93
Metal (wt.%)	3.35	5.12	0.4	0.54	0.3	2.9	0.4	0.23
Wood and bamboo (wt.%)	1.34	2.76	3.3	4.52	0.1	0.9	1.7	1.36
Others (wt.%)	0.11	1.03	——	0.07	——	——	——	——
Recyclables (wt.%)	58.22	55.69	——	38.34	——	——	——	24.31

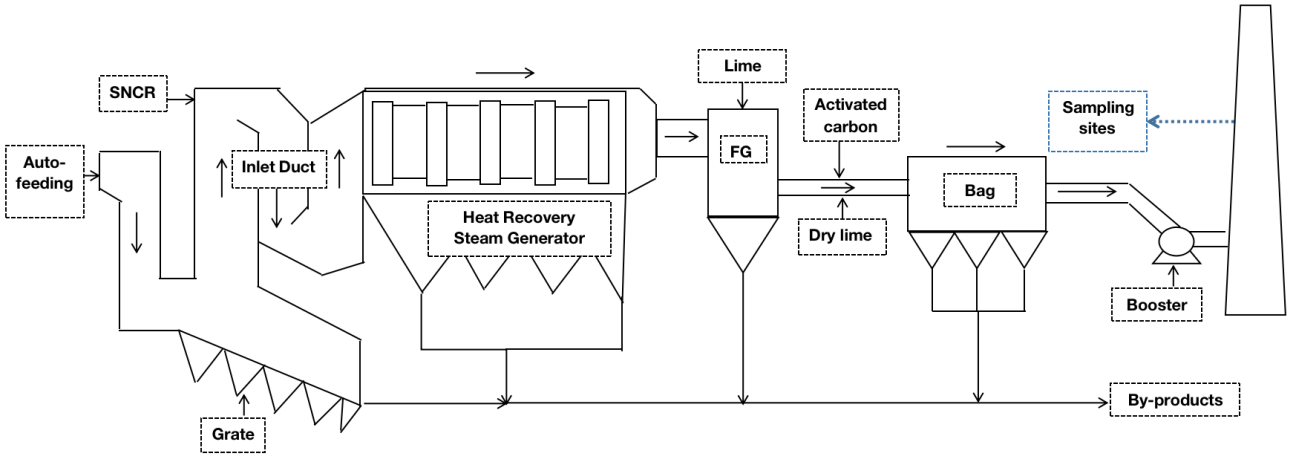
Ash content (wt.%)	27.02	38	——	——	20.34	——	——	——
LHV (kJ/kg)	5994	7877	5083	5800	3552	——	——	——
Reference	Experimental data	Dan and Han, 2012	Li et al., 2010; Wang and Wang,2013	Dong and Zhang,2016	Zhuang et al.,2008; Ni et al.,2005	Huang and Liu,2012	Yang et al.,2018	Gou et al.,2012

Note:—— means not applicable.

112

113 **2.2. Introduction of the experimental site**

114 A MSW incineration power plant located in Lhasa was chosen for the experimental investigation. The pre-set
115 processing ability of the plant was 700t/day, mainly dealing with the MSW collected from Lhasa urban and surrounding
116 counties. The MSW incinerator of the power plant was characterized by a grate incineration system. Notably, the actual
117 disposal capacity during operation has not reached the designed processing ability, and this phenomenon was attributed to
118 the limited MSW collection capacity. The process flow of flue gas purification was shown in Fig.1.The combination of
119 processes was as follows. Firstly, SNCR was used to remove NOx in incinerator. Then, a rotating spray reactor ($Ca(OH)_2$)
120 was used to purify acidic gases. The heavy metals and dioxins in flue gas were adsorbed by spraying activated carbon.
121 Next, the bag filter (with dry lime powder) was used for dust removal and for further acid gas removal. Finally, an
122 on-line flue gas monitoring device was installed.



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124

125 Fig.1. Road map of incineration flue gas purification process in power plant

126 **2.3. Method**

In the experiment, 20 groups were set up. Ten data were extracted from each group. The main purpose of the experiment was to detect the purified smoke and dust. Therefore, the sampling point was set in the middle of the chimney in Figure 1. Among them, the testo350 intelligent flue gas sampler was used for flue gas monitoring, which was produced by Testo Instruments International Trading (Shanghai) Co., Ltd. In addition, the testo3008 intelligent dust sampler collector was used for dust monitoring.

The experimental conditions were as follows:

(1) Two groups of parallel experiments were carried out under ordinary conditions (temperature 1000℃, oxygen content 8%, pressure -50Pa).

(2) Incineration was carried out at different temperatures (700℃, 800℃, 900℃). Two groups of experiments were designed for each temperature point, a total of 6 groups of experiments.

(3) Incineration under different oxygen content (3%, 6%, 9%, 12%) in incinerator was carried out. Two groups of experiments were designed for each oxygen content condition, a total of 8 groups of experiments.

(4) Incineration under different pressure (Micro negative pressure close to 0Pa, 50Pa) was carried out. Two groups of experiments were designed for each pressure condition, a total of four groups of experiments.

During the experiment, according to the experimental conditions, the amounts of smoke and dust was monitored after burning for 20 minutes. The flue gas collection time was 15 minutes. According to the setting conditions of the flue gas sampler, 10 data were collected in each group of experiments. The collection time of smoke and dust was set as 5minutes according to the smoke and dust sampler, and only one data can be obtained each time. Therefore, the dust in each group of experiments needs to be collected 10 times, and an average of 10 data were obtained.

2.4. Samples analysis

Incinerator flue gas was sampled according to the national standard of the People's Republic of China (GB5468-91). The emission of flue gas pollutants was analyzed and evaluated, referring to China's pollutant emission standards (Table S3).

3. Results and Discussion

3.1. Comparison of incineration under ordinary conditions in plain area

Data of flue gas emissions from incineration experiments in plain areas was consulted through literature. Then, the pollutants data of flue gas emission in Plateau and plain areas were compared according to "Standard for pollution control on the MSW incineration" GB18485-2014. The main pollutants, such as dust, SO_2, NOx, CO and HCl, discharged from incineration in plain areas were all below the standard values. In the pollutants discharged from incineration in Plateau area, only NOx exceeded the standard value, and the maximum value of NOx was 301.78 mg/m^3.

157 The maximum HCl value was 53.1 mg/m^3 , being closed to the standard value. The results were shown in Table 2.
158 However, the concentration of NOx emitted from waste incineration under ordinary conditions is quite high. The possible
159 reason is that when the experiment time is selected in dry season, the climate on the plateau is drier, so the moisture
160 content of waste on the plateau is low. Therefore, in the experimental process, the combustion temperature also increases,
161 resulting in the increase of fast type and thermal type NOx. Therefore, we try to find the best incineration conditions by
162 changing the incineration conditions such as temperature, oxygen content and furnace pressure as well, so as to make the
163 flue gas pollutants meet the specified emission standards.

164 Table 2 Measured values of flue gas emissions from plains and plateaus (Unit: mg/m^3)

Regions		Dust	SO_2	NOx	CO	HCl	References
Plateau	Lhasa	1.9-3.1	33.6-70.4	256-333.5	2.93-8.4	41.8-53.1	Range
		2.67	49.79	301.78	5.34	48.22	Average value
	Chuzhou	6.0	7.0	150	1.0	1.74	Zhu et al., 2016
Plain	Quanzhou	22.6	34	129	78	2.5	He,2017
		11.8	19	86	33	2.6	
		10.1	10	115	13	3.2	
		14.0	13	92	21	3.7	
		17.5	38	133	24	2.4	
	Shanxi	＜20	67.75	240	——	46	Liu et al.,2016
	Shenyang	19.45	74	200	49	21.2	Liu,2018

Note:——means not applicable.

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166 **3.2. Emission Characteristics of SO_2**

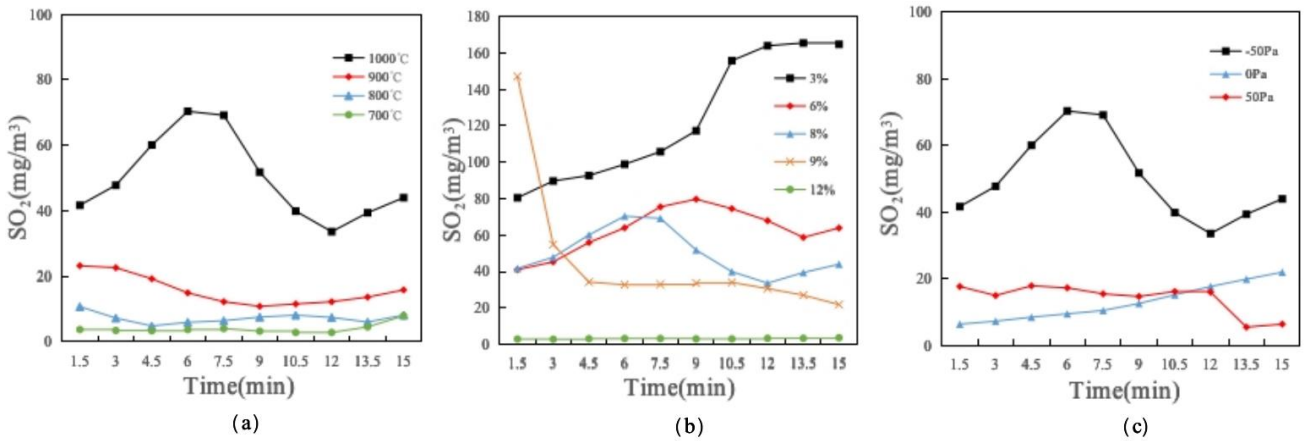

Fig.2. Effects of Temperature, Oxygen Content and Pressure on SO_2 Emission

The emission characteristics of flue gas pollutants caused by the changes of temperature, oxygen content and pressure were shown in Figure 2. During the process of incineration temperature changed from 700ºC to 1000ºC, the oxygen content was 8% and the pressure was -50Pa. It could be seen from Figure 2 (a) that the SO_2 emission concentration increases with the increase of temperature, but the SO_2 emission concentration in flue gas does not exceed the standard limit value of 80mg/m^3. It can be seen from Figure 2(a) that the concentration of SO_2 is the highest at 1000℃. The result of experiment also showed that the SO_2 emission concentration increases with the increase of combustion temperature from 750ºC to 900ºC (Obras-Loscertales et al., 2013). There may be two reasons for SO_2 emission concentration caused by the increase of combustion temperature. First, the weakening of S stability in fuels caused more S precipitation, which leaded to the formation of SO_2 at high temperatures:

$$S+O_2 \rightarrow SO_2 \quad (1)$$

Another reason was that higher temperature inhibited the sulfur fixation of alkali metals and alkaline earth metal oxides in fuel, that would cause an increase in SO_2 concentration (Li et al., 2009).

The change of oxygen content was 3%, 6%, 8%, 9% and 12% when the temperature was 1000ºC and the pressure was -50Pa. From Figure2 (b), it can be seen that the content of SO_2 emission fluctuated greatly. When the oxygen content was 3%, the SO_2 content exceeded the standard limit of 80mg/m^3, and the SO_2 emission concentration increased with the increase of combustion time. When the oxygen content is 3%, a large amount of SO_2 may be produced due to insufficient oxygen supply in the furnace. It was obvious that SO_2 concentration tended to decrease with the increase of oxygen content in the range of 3% to 12% oxygen content. When the oxygen concentration in the furnace is low, the CO concentration in the environment will increase and react with $CaSO_4$, resulting in the re release of SO_2 (Lyngfelt A et al., 1989). Therefore, when the oxygen concentration is low, the following reactions will occur:

$$2CaS+3O_2 \rightarrow 2CaO+2SO_2 \quad (2)$$

$2CaO+2SO_2+O_2 \rightarrow 2CaSO_4$ (3)

$CaSO_4+CO \rightarrow CaO+SO_2+CO_2$ (4)

It has also been shown that with the increase of oxygen concentration, SO_2 emission will be reduced (Czakiert et al., 2012). The reason could be that the increase of oxygen content would cause the formation of SO_2 to combine with oxygen elements to produce SO_3, which would lead to the rapid reduction of SO_2 emissions (Dou et al., 2007;Wan et al., 2007). In addition, the increased of air volume would dilute the concentration of SO_2 emission to reduce SO_2 emission .

From Fig. 2 (c), it could be seen that the SO_2 content produced under pressure of -50Pa was higher than that produced under pressure of 0Pa and 50Pa. The reason may be that the furnace pressure is too low, so that the air coefficient in the furnace increases greatly, the temperature in the furnace also decreases, the combustion speed is slowed down, the thermal efficiency is reduced, and the fuel cannot be fully burned in the combustion process(Zhou and Huang, 2001). Under the above pressure conditions, the emission concentration of SO_2 is within the standard value.

3.3. Emission characteristics of HCl

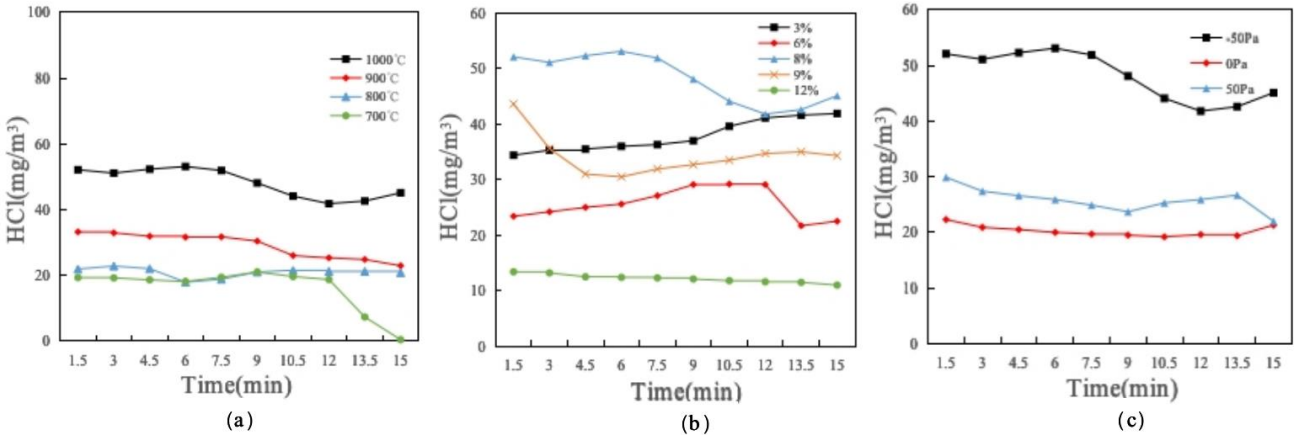

Fig.3. Effects of temperature, oxygen content and pressure on HCl

The effects of temperature, oxygen content and pressure on HCl were shown in Figure 3. When the temperature varied from 700ºC to 1000ºC, the oxygen content was 8% and the pressure was -50Pa. It could be seen from the figure that the HCl content produced at 1000ºC exceeded the standard limit of 50mg/m^3, but was lower than the standard value after a period of incineration time. The figure showed that the concentration of HCl tended to increase with the increase of temperature. The reason for the high HCl emission concentration at high temperature was the high conversion rate of Cl-HCl at high temperature (Jiang et al., 2004). With the increase of temperature, the following reactions are strengthened:

$4HCl+O_2 \leftrightarrow 2Cl_2+2H_2O$ (5)

However, some studies show that there is a temperature turning point in the concentration of HCl. If the temperature

is higher than this point, the emission of HCl will be accelerated; if the temperature is lower than this point, the emission will be reduced quickly (Piao et al., 2000). However, the low emission concentration of HCl caused by low temperature may be due to the decomposition of incomplete incineration products in incineration, resulting in low conversion rate of organic Cl-HCl . Many studies have shown that temperature has a significant effect on the concentration of HCl (Lawrence et al., 2000). In addition, at 600-800℃, CaO will also convert HCl into $CaCl_2$ to reduce the emission of HCl concentration (Liu et al., 2000). However, high HCl content might corrode the metals of incinerator, flue, superheater and other components at high temperature, thus reducing incinerator life and increasing dioxin production .

Figure 3 (b) showed the variation of oxygen content at a temperature of 1000ºC and a pressure of -50Pa. The figure showed that the HCl concentration exceeded the standard limit when the oxygen content was 8%, but it was also lower than the standard value as the incineration time progresses. HCl concentration was the lowest when the oxygen content was 12%. The concentration of HCl tended to decrease with the increased of oxygen content, but the fluctuation was not very large. Some scholars have shown that Cl_2 is easier to form under the condition of oxygen enrichment (Liu et al., 2000). If the formation of Cl_2 is to be well controlled, it is necessary to ensure that there is a lower oxygen concentration in the flue gas.

Fig. 3(c) showed a change in pressure at a temperature of 1000ºC and an oxygen content of 8%. It could be seen in the figure that when the pressure was -50Pa, the HCl production exceeded the standard limit of 50mg/m^3. When the pressure was 0Pa and 50Pa, the concentration of HCl under both conditions was lower than the standard limit. The lowest concentration of HCl is in the state of micro negative pressure when the pressure is close to 0Pa.

3.4. Characteristics of CO Emission and Combustion Efficiency

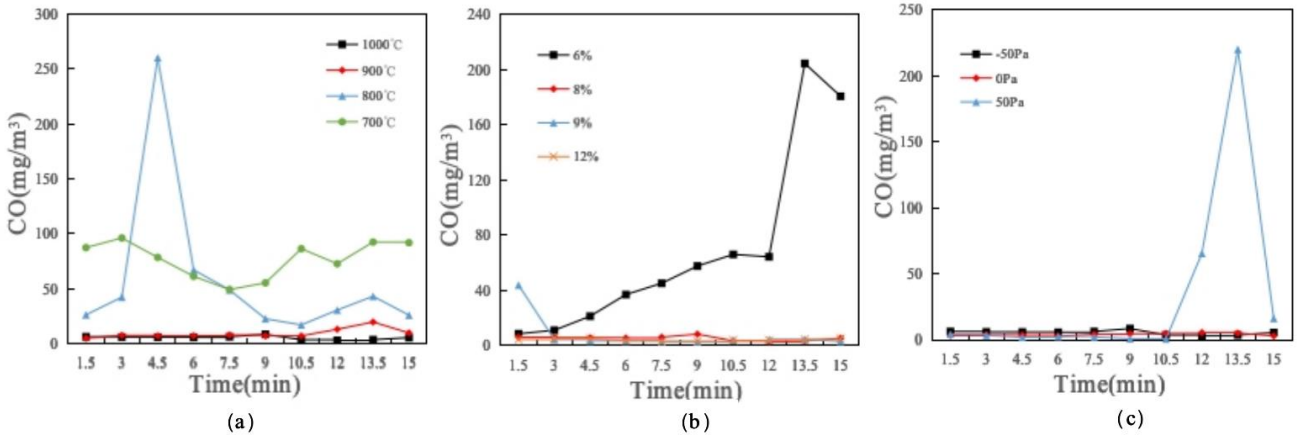

Fig.4. The influence of temperature, oxygen content and pressure on CO emission and combustion efficiency

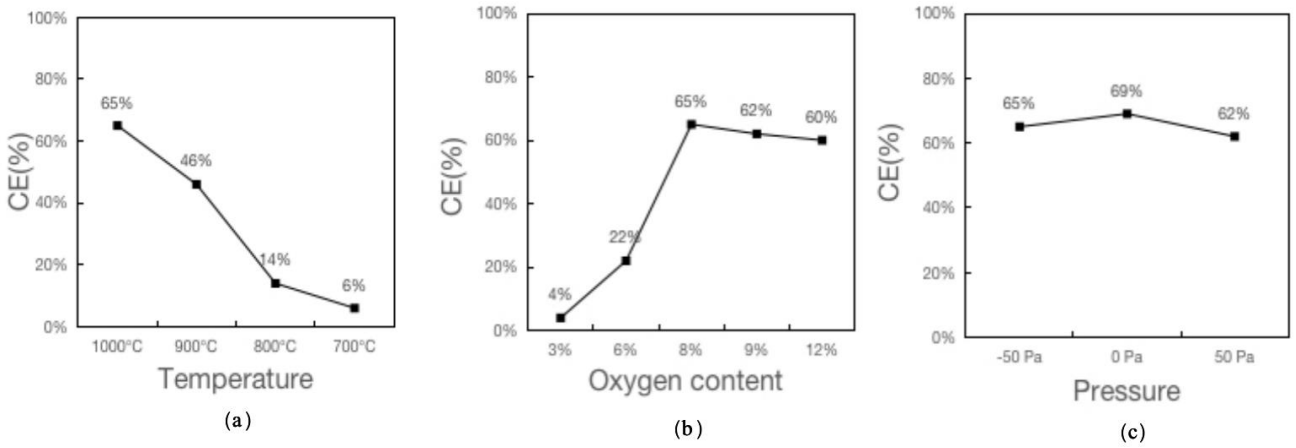

Fig.5. The performance of combustion efficiency under the change of temperature, oxygen content and pressure

The experimental results of CO emission concentration were shown in Fig. 4. However, CO is formed through the separation of volatile matter and the oxidation of C:

$2C+O_2 \rightarrow 2CO$ (6)

$C+H_2O \rightarrow CO+H_2$ (7)

The combustion efficiency refers to the percentage of the mass concentration of CO_2 and the mass concentration of CO_2 and CO in the flue gas. The formula of combustion efficiency was as follows:

$$CE = \frac{\rho(CO_2)}{\rho(CO_2)+\rho(CO)} \times 100\% \quad (8)$$

Here CE meant the combustion efficiency, %. The ρ (CO_2) symbol in the formula was expressed as the mass concentration of CO_2 in the flue gas after incineration, mg/m^3. The ρ (CO) symbol in the formula was expressed as the mass concentration of CO in the flue gas after incineration, mg/m^3. The combustion efficiency is shown in Figure 5.

Firstly, when the temperature varied from 700ºC to 1000ºC, the oxygen content was 8% and the pressure was -50Pa. Figure 4 (a) shows that the emission concentration of CO was lower than the standard limit at temperatures of 1000ºC and 900ºC. However, the emission concentration of CO exceeded the standard limit of 80mg/m^3 at 700ºC. That is to say, with the increase of combustion temperature, the emission concentration of CO decreases. It can also be seen from Figure 5(a) that the higher the temperature, the better the combustion efficiency. Some studies had shown that incineration at high temperature could produce a large amount of HCl, which would consume a certain amount of H, HO, HO_2 radicals. These were necessary products of CO oxidation, thus inhibiting CO oxidation (Xie et al., 2007). This was mainly because the fuel could react completely with the increased of combustion temperature. As a result, the reaction rate and the combustion efficiency of CO were increased, and the CO concentration emission was reduced.

Fig. 4(b) shows the variation of oxygen content at a temperature of 1000ºC and a pressure of -50Pa. In the

experiment, when the oxygen content is 3%, the emission concentration of CO is consistently higher than 300mg/m^3, which has exceeded the maximum value of the instrument. The figure does not show the data when the oxygen content is 3%. This shows that low oxygen content will increase CO concentration emissions. The reason for the high CO emission concentration was that the oxygen content was too low to form oxygen-poor combustion. This would reduce the combustion efficiency, resulting in an increase in CO content. It could be seen from the figure that the concentration of CO decreased gradually with the increase of oxygen content. And the CE value increased with the increase of oxygen content, this shows that the combustion effect was good (in fig.5(b)). If the oxygen content is high, the furnace is fully combusted, thus reducing the oxygen content at the furnace outlet, and finally reducing the CO emission concentration.

The variation of pressure conditions shown in Fig. 4(c) at a temperature of 1000ºC and an oxygen content of 8%. The figure showed that when the pressure was -50Pa and 0Pa, the concentration of CO was below the standard limit of 80mg/m^3. When the pressure was 50Pa, a peak value exceeding 200mg/m^3, but it soon dropped below the standard limit, which might be due to inadequate combustion caused by feeding. From the CE value, the combustion efficiency under the pressure condition was similar except for the extreme value(in fig.5(c)).

3.5. Emission characteristics of NO_X

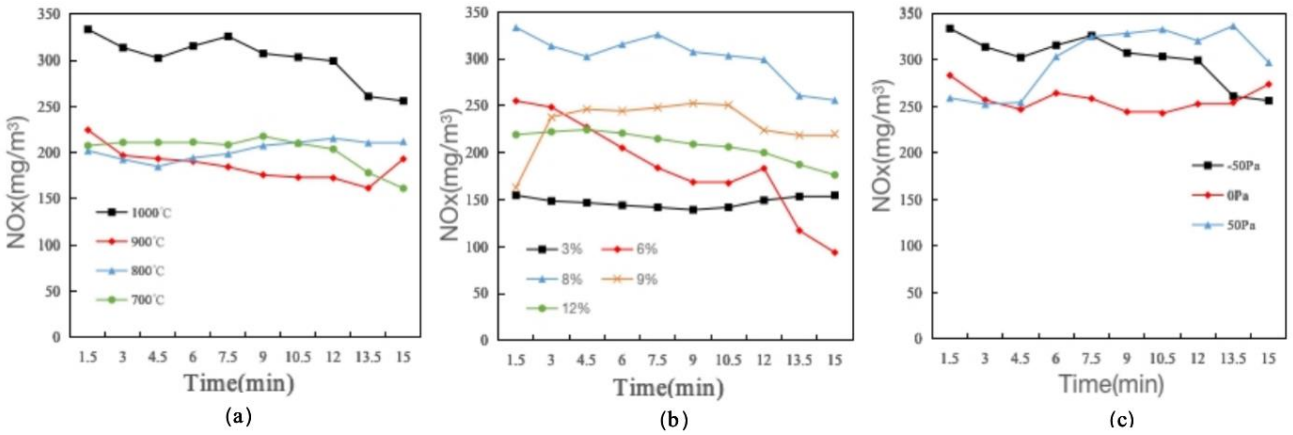

Fig.6. Effects of temperature, oxygen content and pressure on NOx

Fig. 6(a) showed that the experiment was carried out under temperature conditions, at which the oxygen content was 8% and the pressure was -50Pa. It could be seen that the concentration of NOx constantly exceeded the standard limit of 250mg/m^3 at 1000ºC. The concentration of NOx produced at high temperature was higher than that at low temperature. The concentration of NOx increased slowly with the increase of incinerator temperature. However, the generation of NOx was the fuel, the thermal and prompt (Toof J L, 1986). NO could come from the oxidation of volatile N and coke N to form the fuel NO in the process of MSW combustion (Tang et al., 2012). The fuel NOx was related to temperature and

air coefficient. Some studies have shown that a large amount of fast NOx is formed in the combustion environment of low temperature, rich fuel and short standstill time (Toftegaard et al., 2010). However, some studies also showed that the production of thermal NOx increased with the increase of high temperature zone in incinerator. But at a certain temperature, NOx concentration began to decrease (Jin et al., 2007). Increasing incinerator temperature would promote the formation of nitrogen and thermodynamic nitrogen, resulting in higher emission concentration of NOx . Another reason for the high emission of NOx at high temperature was that the combustion rate of volatiles increased with the increase of temperature. Nitrogen compounds were decomposed into NH_3 and HCN by heating, and more NH_3 and HCN were oxidized to NO (Kambara et al., 1993). Therefore, the following reactions occur when the temperature rises:

$$HCN+O \rightarrow NCO+H \quad (9)$$

$$4NH_3+5O_2 \rightarrow 4NO+6H_2O \quad (10)$$

$$NCO+O \rightarrow NO+CO \quad (11)$$

As a result, the emission concentration of thermal NOx also increased. It can be seen that temperature has an obvious effect on NOx emission (Wang et al., 2014).

The variation of oxygen content as showed in Figure 6 (b) was at a temperature of 1000ºC and a pressure of -50Pa. The experimental results showed that the concentration of NOx produced by the experiment with only 8% oxygen content was higher than the standard limit of 250mg/m^3. The figure showed that the oxygen content ranged from 3% to 8%, and the concentration of NOx emission increased with the increase of oxygen content. Oxygen content ranged from 8% to 12%, but the concentration of NOx emission decreased with the increase of oxygen content. The reason was that when oxygen was sufficient in the incinerator, the longer the residence time of the nitrogen element in the fuel in the incinerator, the more NOx oxidation was produced. When the oxygen-poor combustion zone in the incinerator increased, the generation of NOx was inhibited, and the emission was reduced.

Fig. 6(c) showed that the pressure was -50Pa, 0Pa and 50Pa, while the temperature was 1000ºC and the oxygen content was 8%. The concentration of NOx emitted under pressure was higher than the standard limit of 250mg/m^3. However, it can be seen that the NOx concentration at -50Pa and 50Pa is higher than that at 0Pa. One of the reasons may be that the excess gas coefficient increases during combustion under negative pressure, which promotes the formation of fuel type NOx (Zhang et al.,2010). In addition, under the condition of positive pressure, the temperature in the furnace will rise, which will promote the formation of thermal NOx.

3.6. Emission characteristics of dust

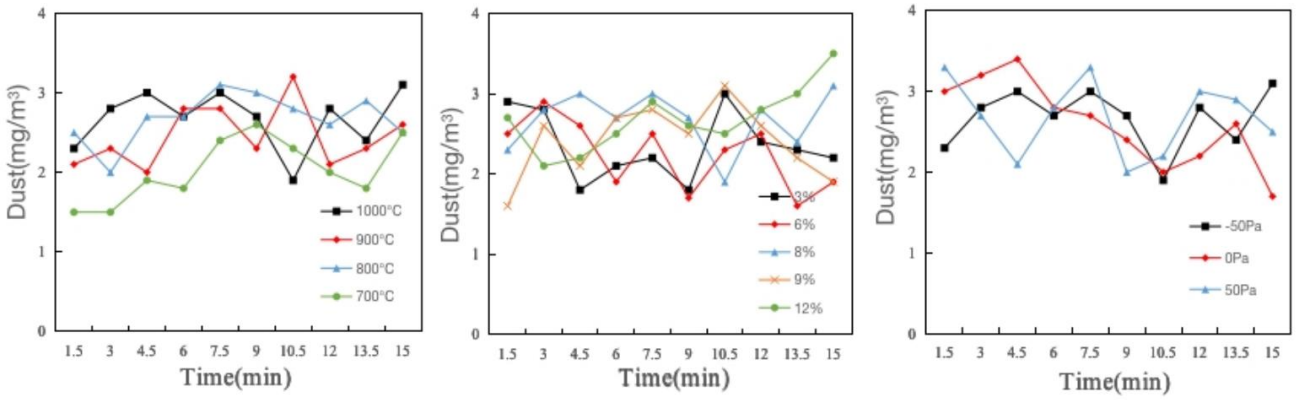

Fig.7. Effects of temperature, oxygen content and pressure on dust

Fig. 7 showed the experimental results of dust under temperature, oxygean content and pressure changed. The emission of dust ranged from 1.9 to 3.1mg/m^3, which was much lower than the standard value of 20mg/m^3. The low emission of dust was due to the use of fabric filter and lime slurry on the surface of the bag for dust removal better. It also showed that the influence of temperature, oxygen content and pressure on dust was not obvious.

3.7. Characteristics of slag and fly ash

（1）Characteristics of municipal solid waste incineration slag

Incineration has the advantages of less land occupation, high volume reduction rate, high degree of reduction, good sanitary conditions, recyclable energy and so on (Yi et al.,2017). However, the slag generated after incineration accounts for 20% - 25% of the total amount of primary waste (Luo et al.,2018;Lu et al.,2018). The slag produced by MSW incineration is mainly composed of glass, ceramics, slag and unburned materials（Wang et al.,2019). Then the heavy metals in the slag are analyzed, and the results are shown in Table S4. It can be seen from the table that the content of Ca in the slag is highest, which may be the reason for the use of lime in bag dust removal. Then, the average value of heavy metals in slag is compared with the heavy metals in slag and soil background value in other areas, as shown in the Table3. The average values of slag in Table 3 are based on the data in Table S4.The content of heavy metals in slag is much higher than the background value of soil in China and Tibet, indicating that the slag can not be directly Dumping at will or landfill. It can be seen from the table that the main heavy metals in slag are Ba, Cu, Zn, Pb, Cr, Ni, etc. Some scholars have studied the municipal solid waste incineration in Beijing found that the main heavy metals in the slag were Ba, Zn, Mn, Cu, Cr and Ni (Lu et al.,2018). It can be seen from the table that the content of heavy metals in the slag in the experiment is different from that in the slag after municipal solid waste incineration in Shanghai. This may be due to the different composition of domestic waste produced in different areas and the different incineration process, which leads to the difference of heavy metal content in the final slag after incineration. However, the huge slag will occupy the land and

pollute the environment. So at present, slag treatment is mainly used for devitrified glass production and building materials utilization (Ferreira et al.,2016;GilA et al.,2014;Khater,2002;Oluwasola et al.,2014;Sharmila et al.,2016).

Table 3 Heavy metal content in waste incineration slag(mg/kg)

Regions / Heavy metal elements	Zn	Cu	Pb	Ba	Ni	Cd	Cr	Mo	As	Se	Hg	References
Average value	815	1000	755	1844	40.4	7.32	253.5	6.07	15.95	0.38	0.10465	Experimental data
Shanghai	228-323	78-221	98-173	—	30-51	1.5-2.8	143-229	—	—	—	—	Zhang et al.,2008
Soil background values in China	74.2	22.6	26	469	26.9	0.097	61	2	11.2	0.29	0.065	Wei et al.，1991
Background value of soil in Tibet	74	21.9	29.1	384	32.1	0.081	76.6	1.1	19.7	0.157	0.024	China environmental monitoring station,1990

Note:——:not applicable.

（2）Characteristics of municipal solid waste incineration fly ash

However, the fly ash from MSW incineration accounts for 2% - 5% of the original MSW, and contains high concentrations of Pb, Zn, Cu, Cr, Ni, Cd and other heavy metals. The fly ash has been listed as hazardous waste in China and many other countries (Fujii et al., 2019;Luo et al.,2018;Phua et al., 2019;Shiota et al., 2017). Therefore, the fly ash in the incineration plant is analyzed, and the results were shown in Table S4. It can be seen from the table that the content of Ca in the fly ash is highest, which may be the reason that lime is used in bag dust removal. Then, the average value of heavy metals in fly ash is compared with that in other parts of China, and the results are shown in the Table 4. The average values of fly ash in Table4 are based on the data in TableS4. It can be seen from the table that the contents of heavy metals Zn, Cu and Pb in the fly ash from the waste incineration in plateau area are similar to those in the fly ash from the waste incineration in plain area. This may be due to the economic development of Tibet in recent years, which leads to a large amount of waste such as electronic products, pigments, batteries and so on. However, the content of Cd

and Hg in the fly ash of plateau area is higher than that of other areas. This may be because Cd and Hg combine with Cl in fly ash to form chlorides, which changes the volatility of metals, resulting in high content of such heavy metals in fly ash (Liang et al.,2014). This also shows that the content of chlorine in the waste in plateau area is higher than that in other areas. The main reason is that the recyclables in domestic waste are high, such as plastic waste is not utilized. Some studies have also shown that the biggest characteristic of waste in China is the high content of chlorine. Direct or indirect contact with heavy metals will produce heavy metal chlorides, which makes heavy metals more easily enriched in fly ash (Yang et al.,2020). In addition, the high content of heavy metal Cd may also be associated with more wastes with high cadmium content in waste, such as nickel cadmium batteries, colored glass, coatings, etc (Xiong et al.,2014). What's more, the content of heavy metal Ba in fly ash is high, which may come from traffic wastes and fossil fuels.

It can be seen from the Table 4 that the fly ash produced in waste incineration varies greatly in different areas. It also shows that the content of fly ash is unstable, which is easily affected by the incineration system and the original waste components. According to China's technical code for sanitary landfill treatment of domestic waste (GB 50869-2013), incineration fly ash is a kind of hazardous waste, which can not be directly put into domestic waste landfill for landfill disposal. Effective measures such as solidification and stabilization must be taken before entering the landfill. Although fly ash is a kind of hazardous waste, it can be used as a resource. For example, the most widely used way for fly ash is to produce cement (Zacco.,2014).

Table 4 Comparison of heavy metal content in MSWI fly ash with that in other areas of China(mg/kg)

Regions / Heavy metal elements		Zn	Cu	Pb	Ba	Ni	Cd	Cr	Mo	As	Se	Hg	References
Average value		3850	275	1050	712	16.5	303	76.7	3.935	50.85	1.37	6.552	Experimental data
Liaoning		3829.6	349.1	—	—	279		601.9	—	—	—	—	Zhang et al.,2019
Hangzhou	1	4582	901.2	1310.8	—	46	127.8	147.7	—	—	—	2.6	Miao et al.,2018
	2	9411.2	1438.9	1343.5	—	53.6	60	296.5	—	—	—	3.2	
Guangxi		1853.5	399.5	266.5	—	—	—	359	—	—	—	—	Kuang et al.,2012
Shanghai	1	2645	298.08	976.61	569.58	34.53	62.47	100.97	—	122.13	6.05	30.18	Ou et al.,2015
	2	3375	490.78	1701.8	591.47	34.25	63	146.21	—	46.89	2.25	7.87	
	3	2777.8	509.3	2257.62	811.92	44.53	56.89	125.43	—	52.72	6.03	21.67	

Shangdong	1	3727.02	331.58	1228.05	485.61	11.12	91.39	73.17	—	84.01	9.24	30.3	
	2	1374.5	224	326.75	589.75	48.4	41	131.25	—	—	—	—	
Sichuan		1358.57	154.71	510.86	139.86	43.73	67.07	98.3	—	—	—	—	
Hubei		5590	390	1770	—	88	100	1.3	—	—	—	—	Liang et al.,2014
Chongqing		461.32	498.44	648.28	—	51.63	111.1	—	—	—	—	—	Liu et al.,2013
Jiangsu		4386	313	1496	—	60.8	25.5	118	—	—	—	52	Zhao et al.,2002

Note:——:not applicable.

4. Conclusions

Based on the analysis of typical components and physical characteristics of waste in Tibet plateau, the results showed that the bulk density of Lhasa domestic waste is 389kg/m^3, the moisture content is 33.8%, and the mean low calorific value is 6935.5kj/kg. The concentrations of SO_2, CO, HCI, dust and NOx in the flue gas discharged under the ordinary condition of low anoxic condition are 49.79mg/m^3, 5.34mg/m^3, 48.22mg/m^3, 2.67mg/m^3 and 301.78mg/m^3 respectively. Then a waste incineration power plant in Lhasa city in Tibet is taken as the experimental object. The characteristics of flue gas emission from incineration of municipal solid waste (MSW) in plateau were investigated under the normal conditions of incineration, and different temperature, oxygen content and pressure in incinerator respectively. Finally, through the analysis of the experimental results and the consideration of the economic cost, it is concluded that the incineration optimum conditions with low pollutant concentration emission were at 900℃, oxygen content of 6% - 8%, and micro negative pressure close to 0Pa.. In addition, the content of heavy metals in fly ash is higher than that in slag.The main heavy metals in fly ash and slag are Zn, Cu, Pb and Ba.

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Author contributions Dan Zeng and Guanyi Chen provided the research ideas and experimental equipment. Wenwu Zhou, Peng Zhou, Qiongda Zhuoma, Jing Wang and Yuechi Che completed the experimental operation and the arrangement and processing of experimental data. A Qiong, Zhiyong Han, Xuebin LV and Bu Duo revised the article. Wang Yang provided some infrastructure in the experiment.

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Data Availability All relevant data are within the manuscript and available from the corresponding author upon request. Supplementary information is available at Environmental Science and Pollution Research's website.

Compliance with ethical standards

Ethical approval This paper is a study on the detection of flue gas emission from waste incineration plant, not involving human and animal research.

Consent to participate All authors were participated in this work.

Consent to publish All authors agree to publish.

Conflict of interest The authors declare that they have no conflict of interest.

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Figures

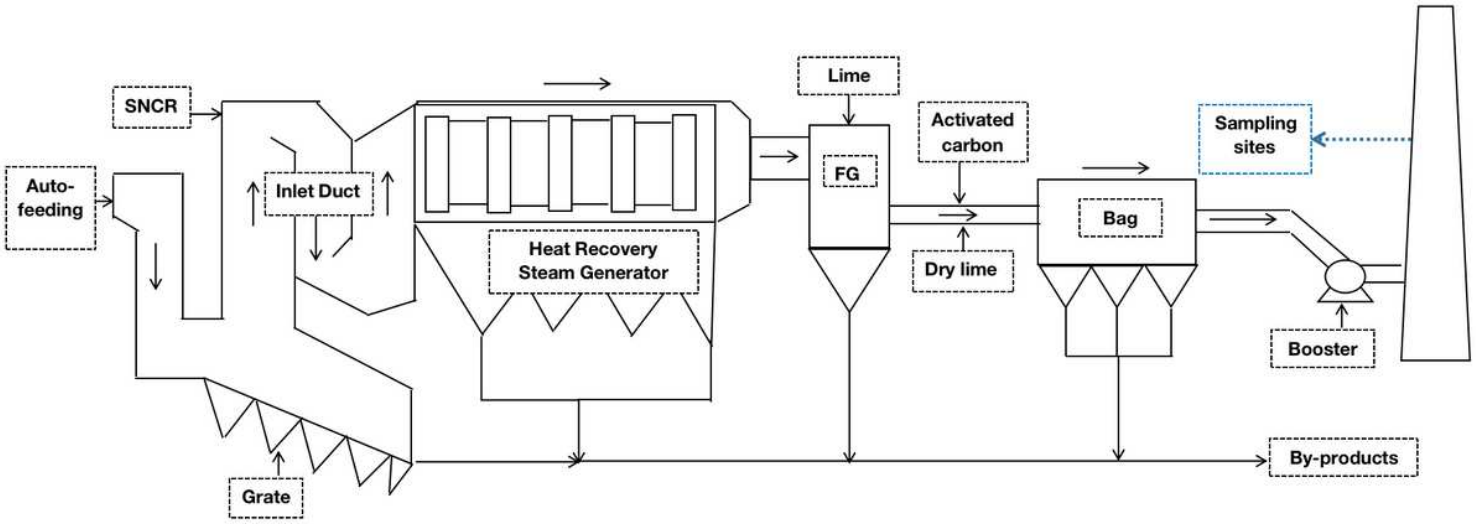

Figure 1

Road map of incineration flue gas purification process in power plant

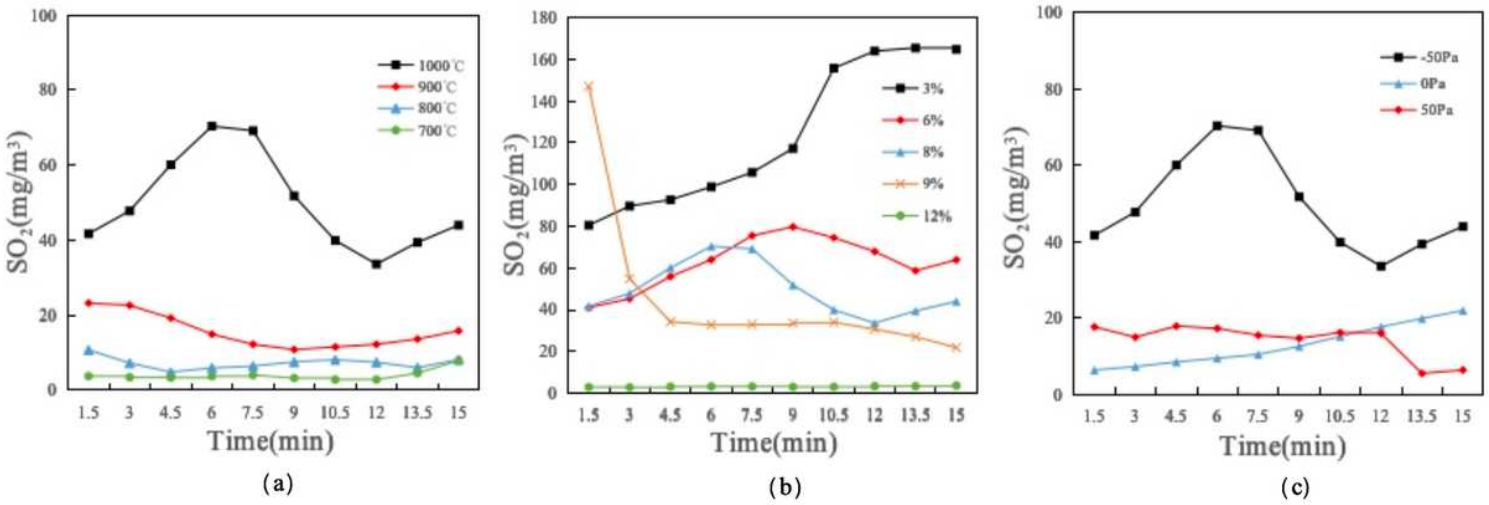

Figure 2

Effects of Temperature, Oxygen Content and Pressure on SO2 Emission

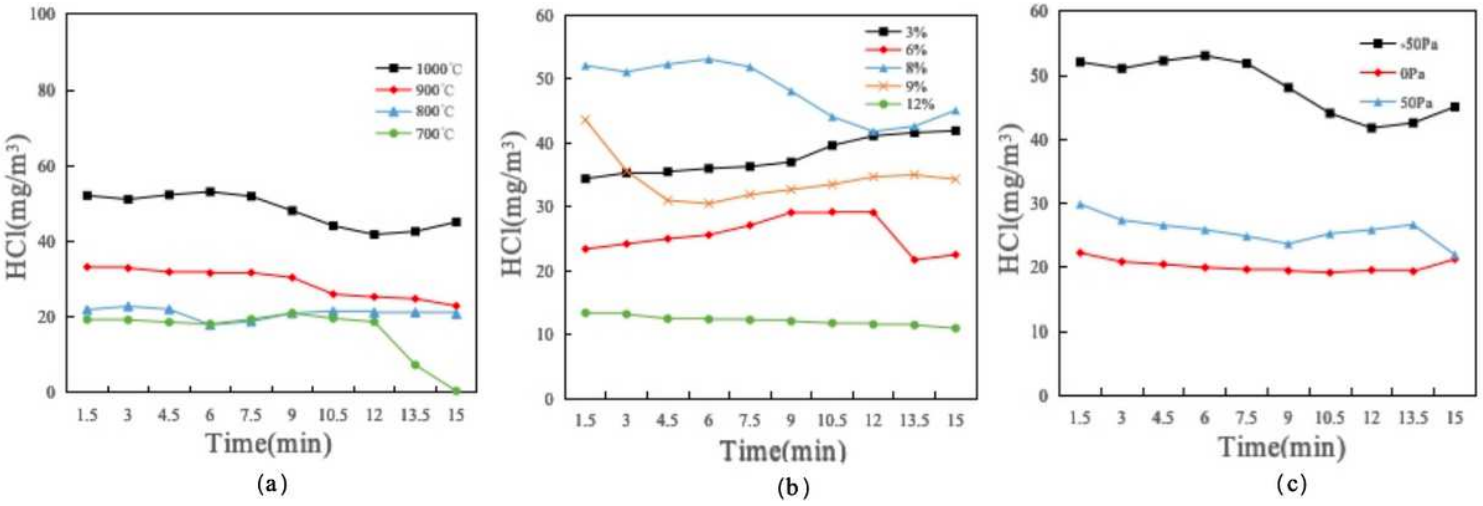

Figure 3

Effects of temperature, oxygen content and pressure on HCl

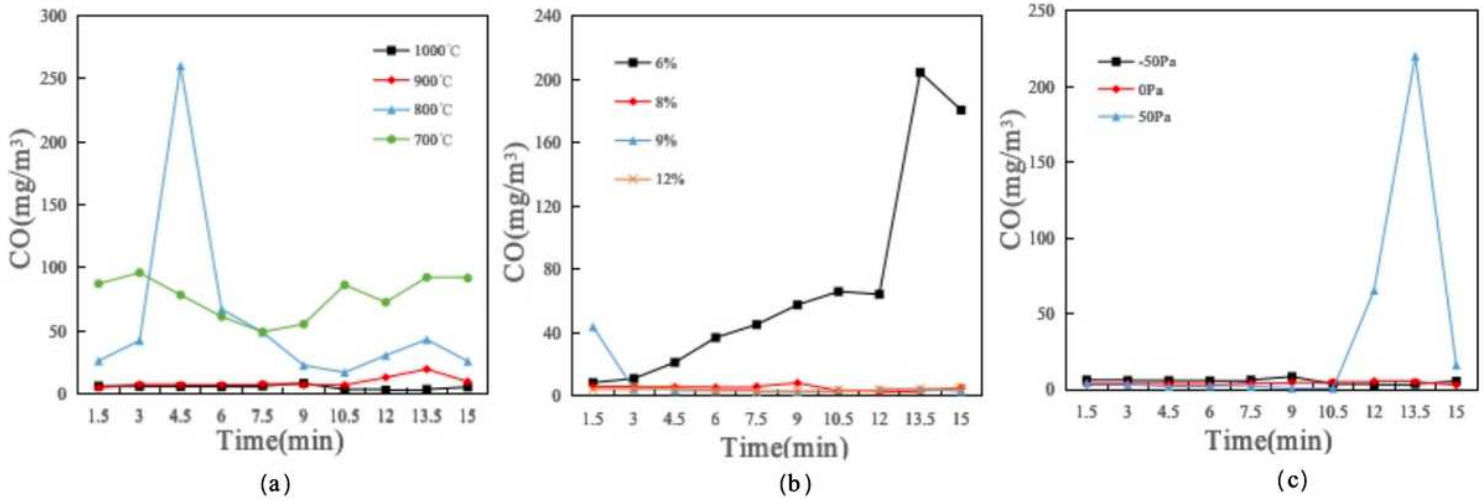

Figure 4

The influence of temperature, oxygen content and pressure on CO emission and combustion efficiency

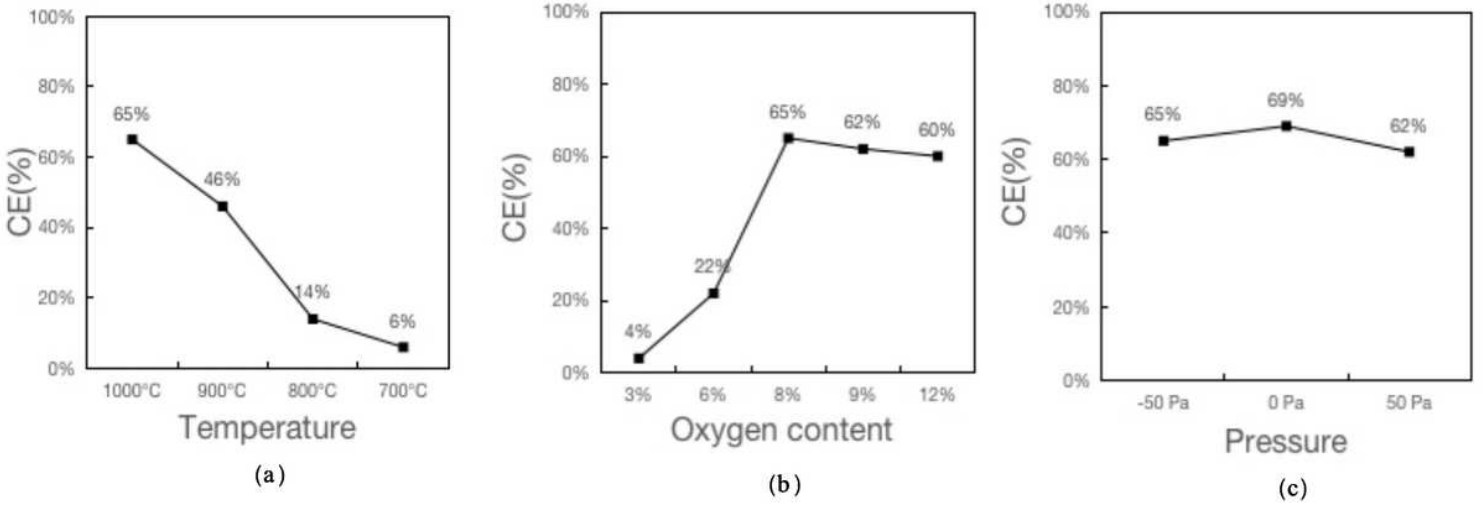

Figure 5

The performance of combustion efficiency under the change of temperature, oxygen content and pressure

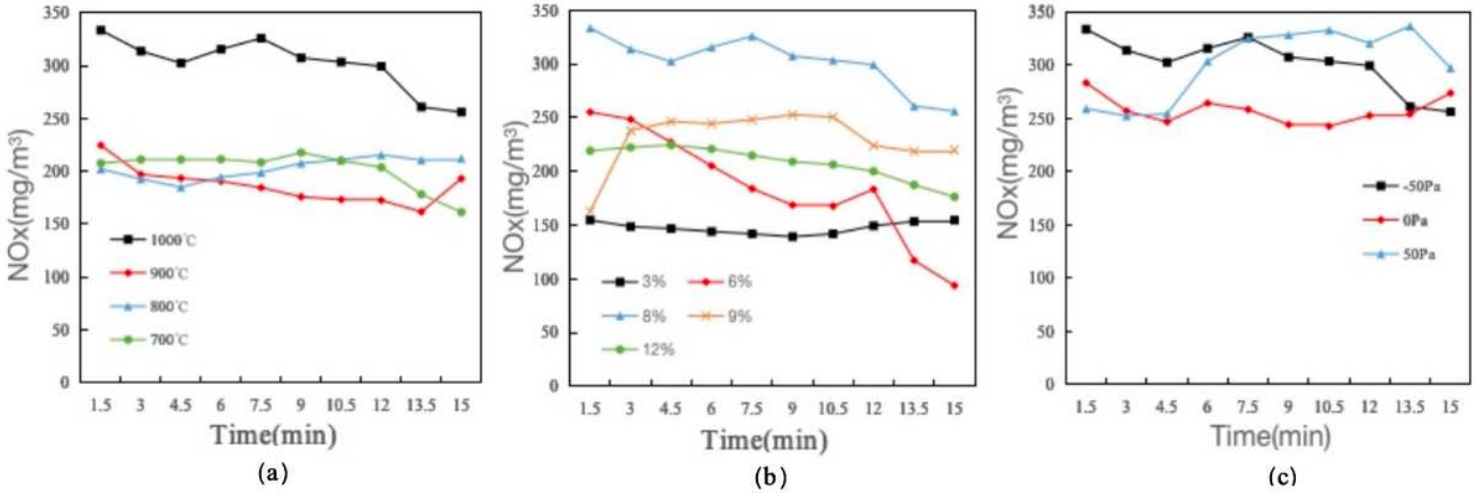

Figure 6

Effects of temperature, oxygen content and pressure on NOx

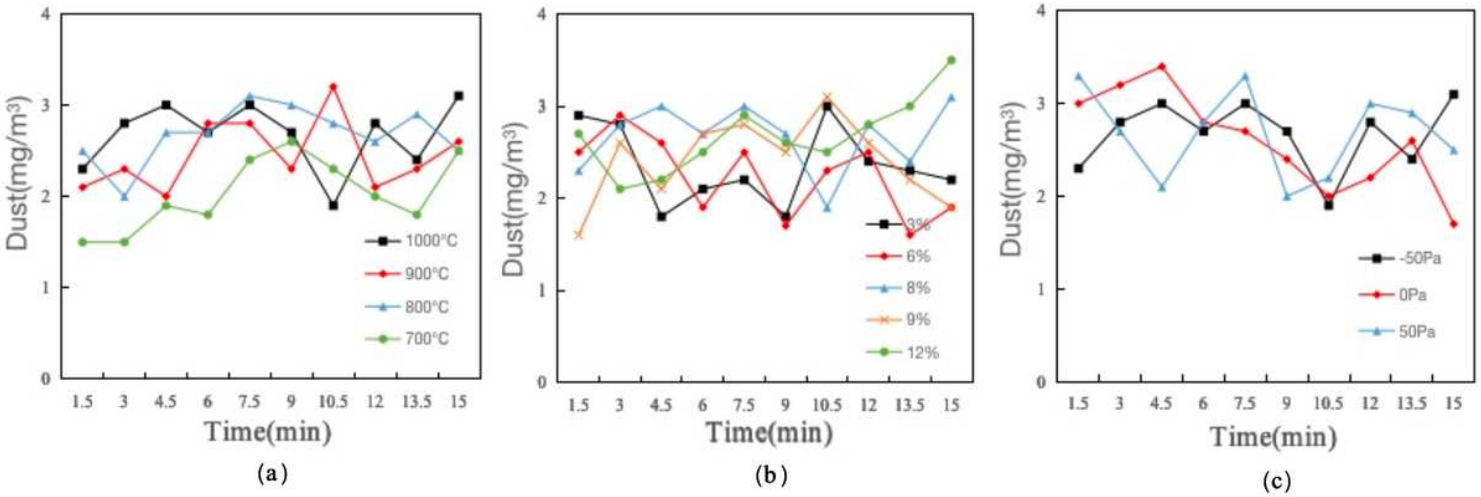

Figure 7

Effects of temperature, oxygen content and pressure on dust

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- GraphicalAbstract.png
- Supplementarymaterial.doc