Characterization of municipal solid waste incineration and flue gas emission under anoxic environment in Tibet Plateau

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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 800 and 900°C. A slight negative pressure in incinerator was benefit for incineration system safety and flue gas emissions. The optimal range was −50 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 N₂ 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

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 SO₂, CO, HCl, dust, and NOx in the flue gas discharged under the ordinary condition of low anoxic condition are 49.79mg/m³, 5.34mg/m³, 48.22mg/m³, 2.67mg/m³, and 301.78mg/m³ respectively.
- The optimal incineration conditions with low pollutant emission were at temperature 900°C, 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.

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 and Horvay 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. 2006). 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 (Dou 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 SO2 emission concentration increased with the increase of air excess coefficient, while the SO2 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, many scholars have studied the pollutants (CO, NOx, SO2, HCl) produced in the process of MSW incineration, and obtained the corresponding data. It has a good reference for the study of the flue gas pollutants from the plateau MSW incineration.

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. In the process of waste incineration, the combustible components in the waste will react with oxygen in the air violently, so the oxygen content in the air plays a decisive role in the whole combustion process. Due to the special natural environmental characteristics of Tibet, especially the low air pressure, low oxygen content in the air, low temperature, and so on, there is an inevitable relationship between natural environmental factors and waste incineration in plateau area. In plain areas, the atmospheric pressure is a standard atmospheric pressure, that is 101.325kpa. However, in the plateau, the atmospheric pressure is only 60% of that in the plain area (at an altitude of 4000 m), which means that the atmospheric pressure in the plateau environment is only 60 kPa. Therefore, if the air is blown according to the common air intake in plain areas, the air intake in plateau areas cannot meet the air volume required for normal incineration. 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. If the air intake is the same as that required by the incineration process in the plain area, the oxygen required for the incineration process in the plateau area is insufficient, the incineration reaction is insufficient, and the incineration efficiency is also low. In addition, incineration is a high-temperature closed combustion process of garbage in the incinerator, and the air required for incineration is continuously sent from the air to the incinerator through an external blower. So, the external ambient air temperature will have a certain impact on the incineration system. Therefore, waste incineration in plateau area is faced with practical scientific problems and engineering application technical problems, such as whether the combustible components in domestic waste and oxygen in the air can be fully burned, the characteristics of flue gas components, the effectiveness of flue gas purification measures, and whether the flue gas can meet the emission standard. To sum up, the special natural environment conditions such as low atmospheric pressure, low oxygen content in the air, and low temperature will have a certain impact on the incineration efficiency and the generation and emission of incineration flue gas in plateau area.

In this work, the emission characteristics of flue gas pollutants (SO2, HCl, CO, NOX, CO2, dust) produced by MSW incineration plant of Lhasa were investigated. This paper analyzes the characteristics of flue gas emission of typical waste incineration process in plateau area through experimental research. In the experiment, the main possible factors such as the pressure in the incinerator, the oxygen content in the incinerator, and the temperature of the incinerator were adjusted, and the influence of the main factors on the flue gas of waste incineration in plateau area was 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. 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.

**Materials and methods**

**Municipal solid waste characteristics**

The physical characteristics of MSW from Lhasa MSW incineration power plant were analyzed; the results were shown in
Table 1. 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. Furthermore, 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 organic matter. It can also be seen from the table that the moisture content of municipal solid waste in Lhasa is 33.8%, which is significantly lower than that in other regions of China, and which is conducive to waste incineration. The low water content may be due to the dry climate, low precipitation, and small vegetation coverage. The low calorific value is 5994kJ/kg in rainy season and 7877kJ/kg (Dan and Han 2012) in dry season. The average low calorific value of Lhasa municipal solid waste is 6935.5kJ/kg, which is higher than the average low calorific value of 5000kJ/kg stipulated in the technical policy of municipal solid waste treatment and pollution prevention. For incineration technology, low/water content and higher low calorific value were the most obvious advantages of Lhasa MSW.

Introduction of the experimental site

A MSW incineration power plant located in Lhasa was chosen for the experimental investigation. The pre-set processing ability of the plant was 700t/day, mainly dealing with the MSW collected from Lhasa urban and surrounding counties. The MSW incinerator of the power plant was characterized by a grate incineration system. Notably, the actual disposal capacity during operation has not reached the designed processing ability, and this phenomenon was attributed to the limited MSW collection capacity. The process flow of flue gas purification was shown in Fig. 1. The combination of processes was as follows. Firstly, SNCR was used to remove NOx in incinerator. Then, a rotating spray reactor (Ca(OH)2) was used to purify acidic gases. The heavy metals and dioxins in flue gas were adsorbed by spraying activated carbon. Next, the bag filter (with dry lime powder) was used for dust removal and for further acid gas removal. Finally, an on-line flue gas monitoring device was installed.

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 testo 350 intelligent flue gas sampler was used for flue gas monitoring, which was produced by Testo Instruments International Trading (Shanghai) Co., Ltd. In addition, the testo 3008 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 °C, oxygen content 8%, pressure 50Pa).
(2) Incineration was carried out at different temperatures (700 °C, 800 °C, 900 °C). 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 pressures (Micro negative pressure close to 0Pa, 50Pa) was carried out. Two groups of experiments were designed for each pressure condition, a total of 4 groups of experiments.

During the experiment, according to the experimental conditions, the amounts of smoke and dust were monitored after burning for 20 min. The flue gas collection time was 15 min. 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 5min 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.

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).
Table 1  Physical characteristics of waste

| Characteristics          | Lhasa incineration plant | Experimental site | Other Cities |
|--------------------------|--------------------------|-------------------|--------------|
|                          | Lhasa                    | Beijing           | Shanghai     | Hangzhou     | Chengdu   | Guangzhou | Lanzhou |
| Bulk density (kg/m³)     | 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       | 2.1     | 6.2   |
| 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; Dong and Zhang 2016; Zhang et al. 2008; Huang and Liu 2012; Yang et al. 2018; Gou et al. 2012

— means not applicable
Results and discussion

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

Emission characteristics of SO$_2$

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 700 to 1000°C, the oxygen content was 8% and the pressure was $-50$Pa. It could be seen from Figure 2a 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 2a that the concentration

| 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 | Zhu 2016      |
| Plain    |      |        |      |      |      |                |
| Chuzhou  | 6.0  | 7.0    | 150  | 1.0  | 1.74 | He 2017        |
| Quanzhou | 22.6 | 34     | 129  | 78   | 2.5  |                |
| 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       |

— means not applicable
of SO₂ is the highest at 1000 °C. The result of experiment also showed that the SO₂ emission concentration increases with the increase of combustion temperature from 750 to 900°C (Obras-Loscertales et al. 2013). There may be two reasons for SO₂ emission concentration caused by the increase of combustion temperature. First, the weakening of S stability in fuels caused more S precipitation, which led to the formation of SO₂ at high temperatures:

\[
S + SO_2 \rightarrow SO_3
\]  

(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 SO₂ concentration (Li et al. 2009).

The change of oxygen content was 3%, 6%, 8%, 9%, and 12% when the temperature was 1000°C and the pressure was −50Pa. From Figure 2b, it can be seen that the content of SO₂ emission fluctuated greatly. When the oxygen content was 3%, the SO₂ content exceeded the standard limit of 80mg/m³, and the SO₂ emission concentration increased with the increase of combustion time. When the oxygen content is 3%, a large amount of SO₂ may be produced due to insufficient oxygen supply in the furnace. It was obvious that SO₂ 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 CaSO₄, resulting in the release of SO₂ (Lyngfelt and Leckner 1989). Therefore, when the oxygen concentration is low, the following reactions will occur:

\[
2CaS + 3O_2 \rightarrow 2CaO + 2SO_2
\]  

(2)

\[
2CaS + 3O_2 \rightarrow 2CaO + 2SO_2
\]  

(3)

\[
CaSO_4 + CO \rightarrow CaO + SO_2 + CO_2
\]  

(4)

It has also been shown that with the increase of oxygen concentration, SO₂ emission will be reduced (Czakiert et al. 2012). The reason could be that the increase of oxygen content would cause the formation of SO₃ to combine with oxygen elements to produce SO₂, which would lead to the rapid reduction of SO₂ emissions (Dou et al. 2007; Wan et al. 2007). In addition, the increased of air volume would dilute the concentration of SO₂ emission to reduce SO₂ emission.

From Fig. 2c, it could be seen that the SO₂ 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 SO₂ is within the standard value.

**Emission characteristics of HCl**

The effects of temperature, oxygen content, and pressure on HCl were shown in Figure 3. When the temperature varied from 700 to 1000°C, the oxygen content was 8% and the pressure was −50Pa. It could be seen from the figure that the HCl content produced at 1000°C exceeded the standard limit of 50mg/m³, 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:

\[
4HCl + O_2 \rightarrow 2Cl_2 + 2H_2O
\]  

(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 and Bu 2000). In addition, at 600–800°C, CaO will also convert HCl into CaCl₂ 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 3b showed the variation of oxygen content at a temperature of 1000°C 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 Cl₂ is easier to form under the condition of oxygen enrichment (Liu et al. 2000). If the formation of Cl₂ is to be well controlled, it is necessary to ensure that there is a lower oxygen concentration in the flue gas.

Fig. 3c showed a change in pressure at a temperature of 1000°C 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/m³. 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.

Characteristics of CO emission and combustion efficiency

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:

\[
\begin{align*}
2C + O_2 & \rightarrow 2\text{CO} \\
\text{C} + \text{H}_2\text{O} & \rightarrow \text{CO} + \text{H}_2
\end{align*}
\]
The combustion efficiency refers to the percentage of the mass concentration of CO₂ and the mass concentration of CO and CO₂ in the flue gas. The formula of combustion efficiency was as follows:

$$CE = \frac{\rho(CO_2)}{\rho(CO_2) + \rho(CO)} \times 100\%$$  \hspace{1cm} (8)

Here CE meant the combustion efficiency, %. The $\rho(CO_2)$ symbol in the formula was expressed as the mass concentration of CO₂ in the flue gas after incineration, mg/m³. The $\rho(CO)$ symbol in the formula was expressed as the mass concentration of CO in the flue gas after incineration, mg/m³. The combustion efficiency is shown in Figure 5.

Firstly, when the temperature varied from 700 to 1000°C, 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 1000°C and 900°C. However, the emission concentration of CO exceeded the standard limit of 80mg/m³ at 700°C. 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, HO₂ radicals. These were necessary products of 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 1000°C and a pressure of −50Pa. In the experiment, when the oxygen content is 3%, the emission concentration of CO is consistently higher than 300mg/m³, 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. 5b). 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 is shown in Fig. 4(c) at a temperature of 1000°C 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/m³. When the pressure was 50Pa, a peak value exceeding 200mg/m³, 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. 5c).

Emission characteristics of 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/m³ at 1000°C. 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 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 NH3 and HCN by heating, and more NH3 and HCN were oxidized to NO (Kambara et al. 1993). Therefore, the following reactions occur when the temperature rises:

\[ \text{HCN} + \text{O} \rightarrow \text{NCO} + \text{H} \]  
(9)

\[ 4\text{NH}_3 + 5\text{O}_2 \rightarrow 4\text{NO} + 6\text{H}_2\text{O} \]  
(10)

\[ \text{NCO} + \text{O} \rightarrow \text{NO} + \text{CO} \]  
(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 6b was at a temperature of 1000°C 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/m³. 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 results shows that the oxygen content in the exhaust gas is less than 7–8%, and the NOx emission increases with the increase of oxygen concentration, and when the oxygen content is more than 7–8%, NOx emission decreases with the increase of oxygen concentration (Wang et al. 2005). In addition, the thermal NOx begins to increase with the increase of oxygen content, and after reaching a certain value, the oxygen content increases and the concentration decreases (Zhou et al. 1998).

Fig. 6c showed that the pressure was −50Pa, 0Pa, and 50Pa, while the temperature was 1000°C and the oxygen content was 8%. The concentration of NOx emitted under pressure was higher than the standard limit of 250mg/m³. 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.

**Emission characteristics of dust**

Fig. 7 showed the experimental results of dust under temperature, oxygen content, and pressure changed. The concentration of dust ranged from 1.9 to 3.1mg/m³, which was much lower than the standard value of 20mg/m³. 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.

**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 Table 3. 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 cannot 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 compositions of domestic waste produced in different areas and the different incineration process, which lead 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; Gil et al. 2014; Khater 2002; Oluwasola et al. 2014; Sharmila and Dhinakaran 2016).

(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 Table 4 are based on the data in Table S4. 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, and coatings (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 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
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  | --- | 30  | 51  | 1.5 | 2.8  | 143  | 229 | Zhang et al. 2008          |
| Soil background values in China |                      | 74  | 226 | 26  | 469  | 98  | 221 | --- | 61  | 2    | 11.2 | 0.29 | 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 |

--- not applicable

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 | 1310.8 | 46 | 127.8 | 147.7 | 601.9 | --- | --- | --- | --- | --- | Zhang et al. 2019          |
| Hangzhou  | 1                    | 4582 | 901.2 | 1310.8 | 46 | 127.8 | 147.7 | 601.9 | --- | --- | --- | --- | --- | Miao et al. 2018            |
|           | 2                    | 9411.2 | 1438.9 | 1343.5 | 53.6 | 60 | 296.5 | --- | --- | --- | --- | --- | --- | --- |
| Guangxi   |                      | 1853.5 | 399.5 | 266.5 | --- | --- | --- | 359 | --- | --- | --- | --- | --- | --- | --- |
| 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 | --- | --- | --- | --- | --- | --- | --- |
|          |                      | 3590 | 390 | 1770 | --- | 88 | 100 | 1.3 | --- | --- | --- | --- | --- | --- | --- |
| Hubei     |                      | 461.32 | 498.44 | 648.28 | 51.63 | 111.1 | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Chongqing |                      | 4386 | 313 | 1496 | 60.8 | 25.5 | 118 | --- | --- | --- | --- | --- | 52 | Zhao et al. 2002            |

--- not applicable
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 cannot 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 et al. 2014).

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/m³, the moisture content is 33.8%, and the mean low calorific value is 6935.5kj/kg. The concentrations of SO₂, CO, HCI, dust, and NOx in the flue gas discharged under the ordinary condition of low anoxic condition are 49.79mg/m³, 5.34mg/m³, 48.22mg/m³, 2.67mg/m³, and 301.78mg/m³ 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°C, 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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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.

Declarations

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 for publication All authors agree to publish.

Conflict of interest The authors declare no competing interests.

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