Melting characteristics during the vitrification of MSWI fly ash with a pilot-scale diesel oil furnace

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ABSTRACT

Treatment of municipal solid waste incineration (MSWI) fly ash is becoming an important issue in China. A pilot-scale experiment was carried out to treat MSWI fly ash by using a diesel oil furnace (DOF) for more than 6 months. The effects of melting temperature on volume reduction, weight loss, compositional changes, and toxicity of leach water for molten slag have been investigated and reported. Results indicated that the volume reduction fraction of raw fly ash (RFA) and washed-fly ash (WFA) was 75–80% and the weight loss fraction was 23.8–30% at 1260–1350 °C. During the vitrification, CaO, Al_2O_3, and SiO_2 percentages in fly ash increased as the temperature increased, especially for SiO_2, which was caused by both the decomposition of carbonates or sulfates and the volatilization of metal chlorides because the main components in secondary fly ash collected from fabric filter bags were NaCl and KCl. The leaching concentrations of heavy metals in molten slag were lower than the standard values of TCLP. The releasing levels of dioxin and other pollutants (such as SO_2, HCl, CO, NO_x, etc.) in flue gas were all lower than the Chinese standard.

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1. Introduction

Landfills are known to be the most expedient, inexpensive method to dispose of municipal solid waste (MSW). At present, landfills are the major treatment method in China. However, this simple method has caused various problems such as groundwater pollution from landfill leachate, odor emission, and soil contamination [1]. Moreover, spaces for landfills have become increasingly limited, especially in countries with a large population. Thus, in recent years, municipal solid waste incineration (MSWI) has become a popular method to treat MSW in places such as Japan and several European countries as the method has the merits of volume reduction up to 90% [2,3] and recovery of much of the energy bound in the waste. By 2006, there were about 42 MSWI plants with a total yearly treatment capacity of 11.2 million tons in China.

Nevertheless, MSWI generates a large amount of fly ash up to the proportion of 3–5 wt% of the original waste amount. Due to the presence of leachable heavy metals, high concentrations of soluble salts, and residual amounts of hazardous organics (e.g., dioxins), [2], this waste is classified as hazardous in many countries and must be treated prior to disposal [4–8]. These hazardous substances in fly ash can pollute groundwater and soils. Some of them are difficult to degrade, they accumulate and are harmful to organisms when exposed. Thus, fly ash must be detoxified or decontaminated prior to disposal or reuse.

At present, various approaches, which mainly include cement fixation, acid extraction, vitrification, and stabilization with chemical agents, have been used to solidify/stabilize fly ash [9]. Compared with other technologies, vitrification is preferred by many countries due to volume reduction and weight loss of residues to landfill, decomposition of dioxins, reuse of molten residue, and reduction of metal leachability. Except for vitrification, it is difficult to apply other techniques to treat MSWI fly ash for the high concentrations of chlorine compounds, such as dioxins and alkali chlorides. Dioxins are difficult to remove or stabilize by cementation or chemical treatment, and alkali chlorides hinder the hydration of cement [1,10].

A number of studies have been focused on the vitrification of MSWI fly ash [11,12]. However, such laboratory studies, while useful, cannot accurately represent real incineration conditions. Therefore, the characteristics of MSWI ashes should be further studied. The aim of this work was to investigate the melting characteristic of fly ash. In this paper, a pilot-scale experiment was carried out to treat fly ash from a MSWI plant in Hangzhou City using a diesel oil furnace (DOF) for more than 6 months with a daily

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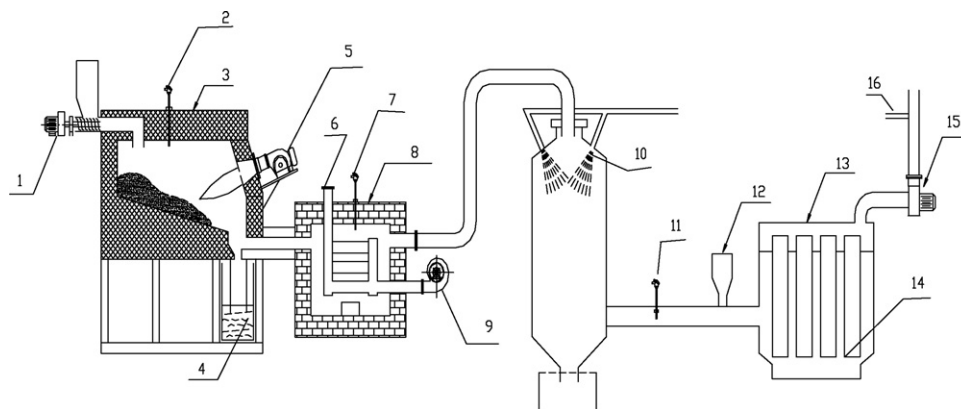[1] Both authors contributed equally to this work.

Fig. 1. Schematic diagram of the pilot-scale molten system for MSWI fly ash. (1) Screw feeder; (2) 2,7,11-thermocouple; (3) furnace; (4) water tank of molten slag; (5) burner; (6) cold air flue; (8) heat exchanger; (9) air compressor; (10) cooling tower; (12) powder gun; (13) bag dust collector; (14) fabric filter bags; (15) centrifugal-induced draught fan; (16) sample collection bore.

treatment capacity of 0.5 tons. The analyzing characteristics mainly include volume reduction, weight loss and compositional change, residual fractions of heavy metals, leach toxicity, and X-ray diffractometer (XRD) of molten slag. Furthermore, dioxins and other pollutants' emission concentrations in flue gas were also measured by the National Research Center for Environmental Analysis and Measurements. The experiment's results and conclusions can provide useful information for the treatment of domestic MSWI fly ash.

2. Experimental apparatus and methods

2.1. Experimental apparatus

In this study, a DOF was used, as shown in Fig. 1, composed of a burning system, a heat exchanging system, a cooling system, and fabric filter bags. It took the furnace 1.5 h to reach 900 °C from room temperature, while it needed 3.5–4 h to reach 1350 °C. The maximum design temperature was 1400 °C.

The temperature provided for melting could be effectively controlled by adjusting the fuel injection pressure and volume. To smoothen the discharge of the circular feed and slag, the feeding began at 1230 °C and the feeding velocities and quantities were controlled by transducer.

The fly ash was held in the DOF at 1260 °C for 15–20 min and then the molten slag was discharged. The DOF could not accurately control the holding time of fly ash, so the effect of melting time on the melting characteristic of fly ash could not be studied in this test. The diesel oil consumption was 5 L/h, melting temperature was 1230–1350 °C, fly ash feeding rate were 20–25 kg/h, and studying temperatures were 1260, 1320 and 1350 °C, respectively.

2.2. Sampling

Two types of fly ashes were used in this study, raw fly ash (RFA) and washed-fly ash (WFA). RFA was taken from a MSWI plant in Hangzhou City. The incinerator was capable of processing 1050 tons of MSW per day. Air pollution control devices equipped in this plant consist of an adsorption reactor and a fabric filter. The RFA was obtained from an initial cyclone and sieved to remove coarse impurities. WFA was obtained as follows: the RFA was washed for 30 min at a liquid/solid (L/S) ratio of 10 L/kg, then the aqueous suspension was filtered through a 45 μm membrane filter and the filtrate collected. The solid residue was air dried and ground through a No. 200 sieve. Small granules screened out were used as WFA.

2.3. Method of measuring the weight loss

Regardless of how long the fly ash was held, there was always a little molten slag retained in the furnace, which can lead to inaccurate results. Each sample (RFA, WFA) was heat-treated at 1260, 1320, and 1350 °C at an amount of about 1 ton to correspond to 2 days capacity, respectively. After one sample was treated for 2 days, the furnace would be left to work further for 3–5 h until there was no slag to flow out. The weight loss was calculated by the following equation:

$$\text{Weight loss (\%)} = \frac{\text{The mass of fly ash sample} - \text{the mass of molten slag}}{\text{The mass of fly ash sample}} \times 100 \tag{1}$$

2.4. Volume reduction

Volume reduction is one of the most important characteristics in the vitrification of fly ashes. However, there is no better method to directly measure the volume reduction except for the measurement of bulk density of fly ash and molten slag. According to the calculation method (Determination of bulk density—Natural bulk method GB/T16913.3-1997, China), the bulk densities of RFA, WFA, and molten slag were calculated, and then the volume reduction was obtained indirectly through the conversion formula. The method applied is summarized below.

The RFA, WFA, and molten slag were grinded and passed through 178 μm standard sieves, dried for 4 h at 105 °C, and cooled to room temperature. Before the experiments, a funnel with the conical angle at 60° ± 0.5° and outflux diameter at Ø 12.7 mm was placed on the level bracket. The funnel center was consistent with the measuring graduate cylinder axis placed underneath, the distance from funnel outflux to the top of the cylinder being 115 ± 2 mm. The graduated cylinder's inside diameter was Ø 39 mm and the volume was 100 cm³. After the outflux was blocked from usage, samples were placed in the funnel, then the stopper was taken out to let the samples fall to the graduated cylinder freely. When the funnel was full, excess samples of the top graduated cylinder were razed with a doctor blade and then weighed.

The experiments were carried out utilizing the same method at least three times, with the difference between the maximum and the minimum weightings smaller than 1 g. Otherwise, tests were carried out until the difference value was smaller than 1 g. The calculated bulk density range was <8.4 g/cm³, and the measurement error was ±0.1 g/cm³.

Fig. 2. Appearance of fly ash before and after vitrification: (a) raw fly ash before vitrification, (b) discharging molten slag after vitrification, and (c) cooled molten slag.

The bulk density was calculated using formula (2):

$$\rho = \frac{m_1 + m_2 + m_3}{3V} \qquad (2)$$

where ρ is bulk density (g/cm^3); m_1, m_2, m_3 are masses measured three times (g); and V is the graduated cylinder volume (cm^3). The volume reduction can be expressed by (3) using the result of formula (2):

$$\text{Volume reduction}\,(\%) = \frac{m_f \times \rho_g - m_g \times \rho_f}{m_f \times \rho_g} \times 100\% \qquad (3)$$

where m_f is the mass of RFA or WFA (g); ρ_f is the bulk density of RFA or WFA (g/cm^3); m_g is the mass of molten slag (g); and ρ_g is the bulk density of molten slag (g/cm^3).

2.5. Toxicity testing

The toxicity characteristic of the leachate was determined according to TCLP, USA EPA Method 1311 SW-846, which is the commonly used toxicity testing method for identification and classification of hazardous wastes by regulatory agencies (US Federal Register, 1980). The TCLP waste classification is based on a much more extensive list of organic and inorganic compounds and covers a broader range of waste types. The toxicity test was performed at $23 \pm 2\,^{\circ}$C using an extraction fluid (pH 2.88 ± 0.05) for the TCLP analysis. This fluid was prepared by adding 5.7 mL of acetic acid to 500 mL of double-distilled water, diluted to a volume of 1 L. A 50 g sample was placed in a 2 L Erlenmeyer flask, and 1000 mL of extraction fluid was added to each Erlenmeyer flask. Samples were then agitated for 18 h using an electric vibrator. At the end of the extraction, the slurry was filtered using a 0.8 µm pore size fiberglass filter and the filtrate liquid was collected to examine the heavy metal concentrations by inductively coupled plasma mass spectrometry (ICP-MS).

2.6. Analyses method

Heavy metals were extracted by an acid mixture of HF, HClO$_4$, and HNO$_3$ (4:1:1) similar to that used by Chan et al. [7]. The heavy metal concentrations were determined by ICP-MS.

X-ray fluorescence (XRF, PW-2402) was performed to analyze the chemical composition of fly ash, molten slag, and secondary fly ash. The specimens were prepared for analysis by mixing 0.4 g of the sample and 4 g of 100 Spectroflux at a dilution ratio of 1:10. Homogenized mixtures were placed in Pt–Au crucibles and treated for 1 h at 1000 °C in an electrical furnace. The homogeneous melted sample was recast into glass beads 2 mm thick and 32 mm in diameter.

The XRD analysis was carried out using a Philips PW-1700 X-ray diffractometer with copper Kα radiation and 2θ scanning, ranging between 5° and 80° (2θ). The XRD scans were run in 0.05° steps, with a 1 s counting time.

3. Result and discussion

3.1. Analyses of main physical phases of slag obtained from fly ashes

In Fig. 2, (a) raw fly ash, (b) furnace when discharging molten slag, and (c) cooled molten slag are shown. Complex physical and chemical changes had taken place in the melting process of fly ash. As fly ash has been pyrolyzed at a high temperature, organic pollutants originating from fly ashes, such as dioxin, are released and metals are partly solidified in the glass matrix of the Si—O structure and partly volatilized into flue gas. The fly ash finally transformed into non-crystalline glass. To better understand the processes of fly ash melting, RFA, WFA, and their slag were analyzed by XRD. As shown in Fig. 3, the XRD patterns of RFA were made up of NaCl, KCl, CaSO$_4$, CaCO$_3$, and SiO$_2$, whereas the XRD patterns of WFA were mainly composed of SiO$_2$, CaCO$_3$, CaSO$_4$, Ca(OH)$_2$, and Ca$_2$Al$_3$SiO$_7$. It could be explained that NaCl and KCl disappeared as soluble salts, while Ca(OH)$_2$ appeared for the hydration of free CaO in washed ash. CaCO$_3$ increased for the carbonation during the washing process. The formation of new mineral species, such as gehlenite (Ca$_2$Al$_2$SiO$_7$), is common in cement.

3.2. Volume reduction

Volume reduction is one of the important parameters in fly ash treatment by melting. However, it is difficult to directly measure the percentage of volume reduction in the pilot scale. We obtained the volume reduction rate by calculating the density change of the fly ash before and after melting at high temperature. Using the
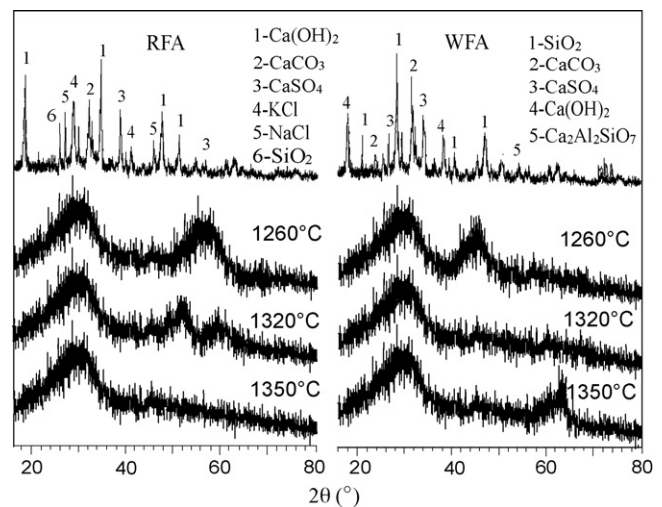

Fig. 3. XRD patterns of fly ash (RFA, WFA) and their molten slag at different temperatures.
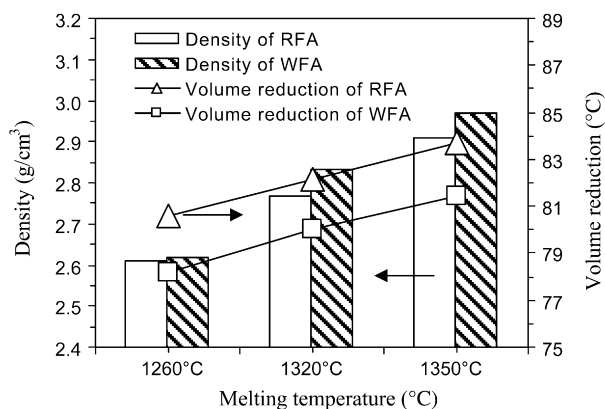
Fig. 4. Effect of melting temperature on volume and density of fly ash (RFA, WFA).

methods given in Section 2.4, the bulk densities of RFA and WFA were found to be 0.664 and 0.705 g/cm³, respectively, and the slag's bulk density at different temperatures was examined by the same method (as shown in Fig. 4). The results shown in Fig. 4 indicate that the densities and volume reduction of RFA and WFA increase with the furnace temperature. After melting at high temperature, volume reduction rate can basically reach up to 80%. The volume reduction rates at 1350 °C can be up to 83.7% and 81.5%, respectively. The fly ash after melting at high temperature was to be sent to a landfill, largely reducing the burden at the landfilling, also an option for reuse as the physical and chemical characteristics of the slag is similar to some building materials [9,13,14]. Therefore, from the point of view mentioned above, high-temperature treatment will become a major method for fly ash treatment, disposal, and reuse.

3.3. Weight loss and main composition change of fly ash

As shown in Table 1, the main components of RFA were CaO, SiO₂, Na₂O, K₂O, Al₂O₃, Fe₂O₃, SO₃, and Cl, among others, accounting for about 82.6% of the total weight. The composition of MSWI fly ash is very complicated and is frequently affected by many factors such as the type of waste, treatment technology, type and operating conditions of the incinerator, and flue gas handling techniques. This pilot-scale experiment manifested the main components of molten slag at 1320 and 1350 °C, as shown in Table 1. The results showed that the contents of CaO, Al₂O₃, and SiO₂ increased with increasing temperature. Compared to other components, SiO₂ percentage was markedly increased. This phenomenon might be caused by two reasons: one is that the glassy matrixes with SiO₂ structure truly increased during the melting process due to the decomposition of some silicates; the other is the relative percentage of SiO₂ increased
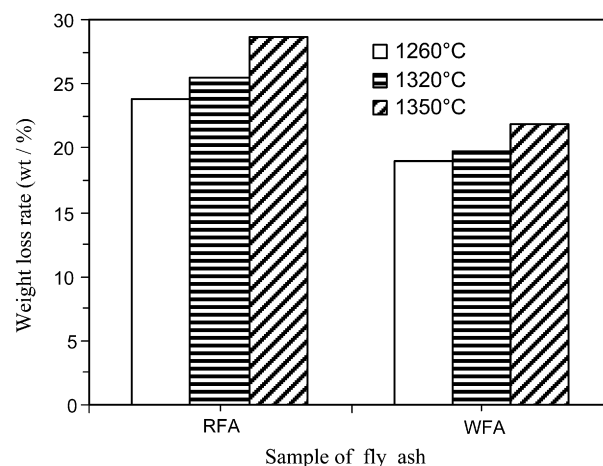

Fig. 5. Effect of melting temperature on weight loss rate of fly ash.

because other compounds (such as metal chlorides) volatilized readily under the high temperature.

XRD revealed that the secondary fly ash collected from fabric filter bags at 1320 °C was mainly composed of NaCl, KCl, and KPb₂Cl₅, as shown in Fig. 6, which confirmed that the metals, such as Pb, K, and Na, vaporized in the form of chlorides. The suggestion proposed by Jakob et al. and Chan et al. [7,15], that heavy metals in fly ash are probably evaporated as chlorides, is supported by this experiment. In terms of the volatilization of chlorides and water and the thermal decomposition of carbonates and sulfates, fly ash lost its weight. As shown in Fig. 5, the weight loss rates of RFA and WFA increased with the rise in temperature. At 1350 °C, the weight loss rates of RFA and WFA were 28.6% and 21.9%, respectively. To gain a better understanding of the characteristics of weight loss, the main chemical composition and XRD pattern of secondary fly ash were investigated by X-ray fluorescence (XRF, PW-2402) and X-ray diffractometer (XRD, PW-1700), respectively. The result showed the main components of secondary fly ash as Cl, Na₂O, and K₂O, accounting for 78.4% of the total volatility (as shown in Table 1). This result was perfectly consistent with the XRD experiments (Fig. 6). On the other hand, the result can further prove that the weight losses of RFA are mainly caused by volatilizations of NaCl, KCl, and some heavy metal chlorides. Otherwise, thermal decomposition of some carbonates, sulfates (for example, CaCO₃ and CaSO₄), and evaporation of H₂O also contribute to their weight losses.

3.4. Residual fractions of heavy metals

In the field experiment, residual fractions of heavy metals in RFA and WFA were investigated between 1260 and 1350 °C, as shown in

Table 1
Chemical composition of fly ash (RFA, WFA) before and after vitrification and secondary fly ash (wt%)

| Chemical composition	RFA				WFA			
	Before vitrification	1320 °C	1350 °C	Secondary fly ash	Before vitrification	1320 °C	1350 °C	Secondary fly ash
CaO	22.8	23.5	25.6	1.3	23.6	18.7	22.2	–
SiO₂	19.8	39.2	43.2	3.2	28.5	48.1	52.5	–
Al₂O₃	7.0	14.1	15.5	2.1	9.8	14.0	14.8	–
Fe₂O₃	4.0	4.0	4.5	1.0	5.3	5.2	4.2	–
Na₂O	6.7	3.7	0.2	23.7	1.6	2.5	0.1	–
K₂O	6.2	1.9	0.7	19.6	2.1	2.6	0.5	–
SO₃	8.7	0.0	0.0	13.4	6.6	0.0	0.0	–
Cl	10.2	0.0	0.0	35.0	1.3	0.0	0.0	–
P₂O₅	2.5	0.0	0.0	0.1	3.6	0.0	0.0	–
MgO	3.8	6.8	7.5	0.0	5.4	4.0	3.6	–
TiO₂	1.2	1.4	1.6	0.0	1.6	1.7	1.8	–
Total	82.6	94.6	98.8	99.4	89.4	96.8	99.7	–
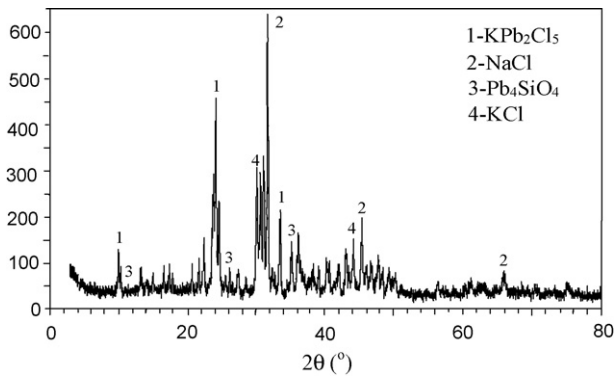
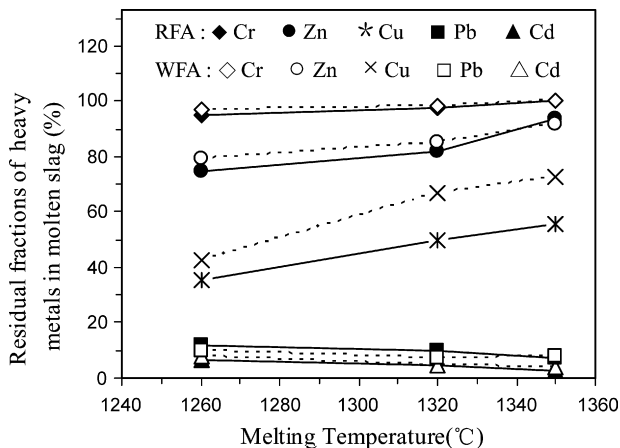**Fig. 6.** XRD patterns of the secondary fly ash.

Fig. 7. Residual fractions of heavy metals in molten slag after vitrification at different temperatures.

Fig. 7. It is considered that elements with high boiling points like Si, Al, and Ca are converted into slag. The substances with low boiling points like Cd and Pb are converted into fly ash or melting furnace exhaust gas [9]. The proportion of heavy metals remaining in slag after melting is defined as "Residuals," which is calculated by the following equation [16]:

$$
\text{Residuals (\%)} = \frac{\text{Concentration in slag after melting} \times (1 - \text{evaporation})}{\text{Concentration in ash before melting}} \times 100
$$

Under high temperatures, glassy phases would be present in pectic state, thus high volatile metallic compounds would vaporize and alkali metals would decompose. As the melting temperature increased, more than 95% of Cr was stabilized in glassy matrixes.

The residual of Zn was up to about 80%, while that of Pb remained at the lowest levels according to the results. The decreasing levels of stabilized heavy metals in molten slag followed the order of Cr > Zn > Cu according to experimental results. For the heavy metals with low boiling points like Pb and Cd, the residues of such materials would almost completely vaporize during the process of two molten samples. Alkali metals chlorides in fly ashes would accelerate the evaporation strength of heavy metals with low boiling points. For Pb, the vaporization fractions in two samples were 99.7% and 99.9% at 1350 °C, respectively. The residual fractions of Cr, Cu, and Zn in WFA were higher than those in RFA, from 1260 to 1350 °C, especially for Cu. The residual fractions of Cu in RFA and WFA were 35.1% and 42.5% at 1260 °C, respectively, and the residual fractions were 55.4% and 72.4% at 1350 °C, respectively.

3.5. Leaching test

The leaching test is an important method for evaluating the immobilization capacity of heavy metals by vitrification and may directly influence the effects of handling and disposal methods. In this experiment, five heavy metal elements (Cd, Cr, Cu, Pb, and Zn) were analyzed with TCLP and, as shown in Table 2, all heavy metal concentrations in the slag were far lower than the specified limits. On the other hand, Cd, Cu, and Pb concentrations of TCLP leachate were even lower than that of the detection limit as the temperature was below 1320 °C. Leachability is dependent on vitrification parameters, mainly vitrification time, temperature, and atmosphere, which function to convert it into a readily soluble form [17], but also on the process of vitrification. In general, heavy metals and/or their compounds in the incinerator ash will evaporate depending on their volatility, temperature, and vitrification time during the vitrification process in the DOF. When the temperature was below 1320 °C, the compounds of Cd, Cu, and Pb were possibly converted to their more extractable hexavalent form, but the possible reasons still remain to be studied. This shows that the leachability of heavy metals in fly ash is a complicated matter.

3.6. Flue gas test

3.6.1. Dioxin in flue gas

The DOF temperature could reach as high as 1350 °C, and dioxins were decomposed effectively at this temperature. The furnace utilized the urgently cool technology for flue gas to control the rebirth of dioxins. The temperature of high-temperature flue gas instantly dropped to below 200 °C from over 600 °C after it passed through a spraying tower and avoided the dioxin synthetic again. On the other hand, the system of fabric filter bags could absorb some residual dioxin effectively. The dioxin concentration in flue gas was investigated by the "National Research Center for Environmental Analysis

Table 2
Leaching concentrations of heavy metal in fly ash and molten slag according to the TCLP method (mg/L)

Melting temperature	Sample	Cd	Cr	Cu	Pb	Zn
Before vitrification	RFA	1.86 ± 0.22	0.28 ± 0.07	8.94 ± 0.17	15.89 ± 0.52	48.95 ± 0.46
	WFA	1.95 ± 0.13	0.34 ± 0.02	5.02 ± 0.29	18.57 ± 0.28	35.82 ± 0.38
1260 °C	RFA	ND	0.37 ± 0.02	ND	ND	12.35 ± 1.08
	WFA	ND	0.45 ± 0.01	ND	ND	8.61 ± 1.52
1320 °C	RFA	0.14 ± 0.02	0.20 ± 0.03	0.35 ± 0.09	0.21 ± 0.02	5.85 ± 1.01
	WFA	0.12 ± 0.05	0.18 ± 0.04	0.20 ± 0.05	0.18 ± 0.01	4.90 ± 1.49
1350 °C	RFA	0.07 ± 0.01	0.73 ± 0.01	0.14 ± 0.02	0.08 ± 0.03	2.29 ± 0.85
	WFA	0.09 ± 0.03	0.82 ± 0.03	0.19 ± 0.10	0.05 ± 0.02	2.05 ± 0.64
Regulatory values		1.0	5	15	5	–

Note: ND: none detected.

Table 3
Analysis results of pollutants in flue gas (mg/m^3)

Test working condition	Results
*Load (%)	100
*Section area of pipeline (m^2)	0.0314
*Temperature of sample points (°C)	60
*Moisture (%)	6.5
*Velocity of flue gas flow (m/s)	3.1
*Oxygen content in flue gas (%)	12.3
*Excess air coefficient	2.41
*Smoke blackness (lindman)	<1
*Field measurement of flue gas (m^3/h)	353
*Dry volumetric stack gas flow rate corrected to standard conditions (m^3/h)	271

Test item	Results	Regulatory values
Particulate	33.1	100
As	3.47×10^{-2}	
Ni	2.17×10^{-2}	1.0
Hg	5.23×10^{-4}	0.1
Cd	6.37×10^{-2}	0.1
Pb	0.870	1.0
Mn	7.18×10^{-2}	
Cu	0.142	4.0
Cr	0.0353	
SO_2	264	400
NO_x	111	500
HCl	3.23	100
CO	1.57	

Note: * measured value in field.
Monitoring method: GB/T16157-1996, China-"The Determination of Particulates and Sampling Methods of Gaseous Pollutants Emitted From Exhaust Gas of Stationary Source".
National standard: GB18484-2001, China-"Hazardous Wastes-Pollution Control Standards of Incineration".

and Measurements" to be 0.053 ng-TEQ/m^3, which was lower than Chinese limit values for dioxin emission. During the testing process, the DOF ran steadily and its treatment capacity was 22 kg/h. Thus, the DOF can effectively decompose dioxin and avoid the production of secondary environmental pollution.

3.6.2. Other pollutants in flue gases

The flue gas contained not only heavy metals and dioxins, but also some other pollutants caused by the combustion of diesel oil, for example, NO_x, SO_2, and CO. If the disposal method was improper, then these pollutants would cause environmental pollution. In this pilot test, flue gas cooling tower, CaO (powder gun), and fabric filter bags were used to control these pollutants. The Hangzhou Environmental Monitoring Center had tested the concentrations of each pollutant according to "GB/T16157-1996, China-The determination of particulates and sampling methods of gaseous pollutants emitted from exhaust gas of stationary source." The results are shown in Table 3. As you can see from the table, all pollutants meet the emission standard of "GB18484-2001, China-Standard for pollution control on the municipal solid waste incineration."

4. Conclusion

The results showed that the weight loss rates of RFA and WFA were 28.6% and 21.9% at 1350 °C, and their volume reduction lev-

els were 83.7% and 81.5%, respectively. With temperature increase, the relative percentage of CaO, $A1_2O_3$, and SiO_2 in RFA and WFA gradually increased, especially for SiO_2, which was caused by both the decomposition of carbonates or silicates and the volatilization of metal chlorides because the main components of secondary fly ash collected from fabric filter bags were NaCl and KCl, accounting for 78.4% of the total weight. The residual levels of stabilized heavy metals followed the order of Cr > Zn > Cu > Cd > Pb in melted slag. Cr content was the highest in the residual fractions of molten slag, up to 95%, followed by Zn up to 80%, while that of Pb was the lowest. The leaching concentrations of all heavy metals in molten slag were far lower than the standard values of TCLP. The concentrations of dioxin and furans (PCDD/Fs) in flue gas were about 0.053 ng-TEQ/m^3, far lower than Chinese limit values for dioxin emission, and the other pollutants in flue gas also meet the Chinese standard (GB18484-2001, China).

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