



Pollution Characteristics of Thermal Treatments for Elutriated Ashes. Part 2: Comparison with Incineration System and Plasma Melting System

Yi-Ming Kuo^{1*}, Jhong-Lin Wu², Jian-Wen Wang¹, Li-Te Yin³

¹ *Department of Safety Health and Environmental Engineering, Chung Hwa University of Medical Technology, Tainan City 71703, Taiwan*

² *Environmental Resource Management Research Center, Cheng Kung University, Tainan City 70955, Taiwan*

³ *Department of Optometry, Chung Hwa University of Medical Technology, Tainan City 71703, Taiwan*

ABSTRACT

This study investigated the pollution characteristics of a plasma melting system and compared its performance with that of the incineration system that was reported in Part 1 of this study. The heavy metals and polychlorinated dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs) in input and output materials during elutriation and plasma melting processes were analyzed. The elutriation process dissolved NaCl and caused an increase in the PCDD/Fs of raw mixed incinerator ashes. After being melted with waste silica gel, the PCDD/F level of elutriated ashes was greatly reduced, and the output mass/input mass ratio was only 0.000188, which was much lower than that of the co-incineration process (0.34). The powdery and porous structure of elutriated ashes was transformed into a glassy amorphous structure after the plasma melting process, and the slag was regarded as a non-hazardous product that can be recycled directly. The concentration of pollutants in the flue gas was much lower than the regulated standards. Although the operational cost of the plasma melting process is higher than that of the incineration process, the plasma melting process has a superior effect on the stabilization of elutriated ashes and is thus a preferable treatment method.

Keywords: Elutriated ash; Stabilization; Slag; Polychlorinated dibenzo-*p*-dioxin and dibenzofuran; Heavy metal.

INTRODUCTION

For the disposal of laboratory waste (LW) from schools, Sustainable Environment Research Center (SERC) of National Cheng Kung University has built an LW treatment plant situated in Tainan City. This LW treatment plant, subsidized by the Ministry of Education, comprises three major systems, including a physicochemical treatment system, an incineration system, and a plasma melting system. The physicochemical treatment system mainly focuses on the treatment of liquid LW. The major target of incineration system is organic solid and liquid LW from medical and biochemical experiments, which usually has Cl levels higher than 10% (Wu *et al.*, 2014). The incineration process of solid waste containing high level of Cl generates a large amount of PCDD/Fs (Hatanaka *et al.*, 2005). The output materials with high level of PCDD/Fs has a noticeable impact on atmosphere and results in secondary pollution through atmospheric deposition (Coutinho *et al.*,

2006; Zhu *et al.*, 2017). In addition, fly ashes contained extremely high level of polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofurans (PCDD/Fs) which are usually up to ten times higher than those of general municipal solid waste incinerators (Gidaracos *et al.*, 2009; Liao *et al.*, 2014; Han *et al.*, 2017). The PCDD/Fs mainly distributed in fly ashes (> 90%) and therefore, how to dispose these fly ashes is an important environmental issue (Wang *et al.*, 2010). The removal of PCDD/Fs using surfactants was reported in a previous study (Liu *et al.*, 2017). Part 1 of this study investigated the feasibility and pollution characteristics of co-incineration of mixed ashes with LW. Raw mixed fly ashes usually contain high level of Cl and, thus, are not suitable to be incinerated directly. The raw mixed fly ashes were elutriated to wash out Cl to reduce the formation of PCDD/Fs during the co-incineration process (Mubeen *et al.*, 2017). This study attempted to treat the elutriated ashes using plasma melting furnace. This plasma melting furnace was used to treat the sludge and the ashes ordinarily from the physicochemical treatment system and incineration system. These hazardous materials were mixed with waste cullet and silica gel and transformed into inner slag (Kuo *et al.*, 2010). The slag can be recycled to be made into a composite with polyester resin (Kuo *et al.*, 2011).

The thermal melting processes (> 1300°C) can be used

* Corresponding author.

Tel.: +886-6-2674567 ext. 854; Fax: +886-6-2675049
E-mail address: kuoyiming@gmail.com

to stabilize hazardous materials, decompose persistent organic pollutants, and recover valuable metals (Huang *et al.*, 2013; Hung *et al.*, 2018). The operational cost is much higher than that of other stabilization technologies but the effect on stabilization of hazardous materials is excellent. The objective of the present study is to evaluate the treatment of elutriated mixed ashes in an alternative approach different from Part 1 (Wang *et al.*, 2016). In this study, the raw mixed ashes was elutriated, mixed with waste silica gel, and melted using the plasma melting furnace. This study focuses on the emission characteristics of PCDD/Fs and metals of the plasma melting system and compares the performances of the two technologies. Here, the PCDD/F, metal, and Cl contents of the input and output materials in the elutriation and plasma melting process were measured. In addition, the distribution of heavy metals and PCDD/Fs in the involved system was also investigated to evaluate its performance.

METHODS

Processes of Elutriating Unit and Plasma Melting System

Raw mixed ashes, collected from the incineration system, were elutriated using water with mass ratio of solid:liquid = 1:10. The elutriating wastewater was drained to the physicochemical treatment system for clarification. The elutriated ashes and waste silica gel were mixed in advance with mass ratio of 10:4, and then was conveyed into the plasma melting furnace at a feeding rate of 125 kg hr⁻¹ through a feeding unit. The process flow chart of the elutriating process and plasma melting system is shown in Fig. 1.

The plasma melting furnace has inner space with dimensions of 1420 mm (ϕ) \times 850 mm (L) and equipped with a plasma torch generator at its top. The plasma torch was generated in a non-transferred type and was carried by

3 Nm³ min⁻¹ of air. The temperature of torch and environment inside the furnace was controlled at \sim 6,000°C and \sim 1450°C, respectively, to ensure that all the input-materials were completely melted. The electricity consumption of the plasma melting system was averagely 52 kW. Molten material was discharged from the bottom outlet into metallic carts and quenched using water to form amorphous slag.

The flue gas emitting from the top of the furnace was treated by serial air pollution control devices, including a Venturi cooling tower, a wet scrubber, and a fixed-bed adsorption tower. The Venturi cooling tower is used to cool the flue gas by water down to 150°C rapidly to suppress the reformation of dioxins. Then, an alkaline solution (40% sodium hydroxide, [NaOH]) was injected into the wet scrubber with a ratio of liquid:gas = 1 L:1 m³ to remove the acid gas pollutants and particulate in the flue gas. Finally, the fixed-bed absorption tower, filled with activated carbon, adsorbed gaseous Hg and other toxic organic substances. The flue gas is then emitted to the pipe of the involved incineration system in Part 1 (Wang *et al.*, 2016). After treating by APCDs again, the flue gas of the incineration system and plasma melting system was emitting through the same stack into ambient air. The wastewater (the amount = 900 L hr⁻¹) from the Venturi cooling tower, scrubber, and elutriating unit was piped to the physicochemical treatment process for further clarification.

Sampling of Flue Gas, Wastewater, and Solid Specimens

The stack flue gas was sampled at the point after fixed-bed adsorption tower in triplicate. The sampling work followed the standard sampling procedure of PCDD/Fs and metals in stack flue gas (Environmental Analysis Laboratory, 2010). The wastewater was filtrated using a mixed cellulose ester filter (ϕ = 47 mm, pore size = 0.8 μ m) and separated into solid phase and water phase. Solid specimens,

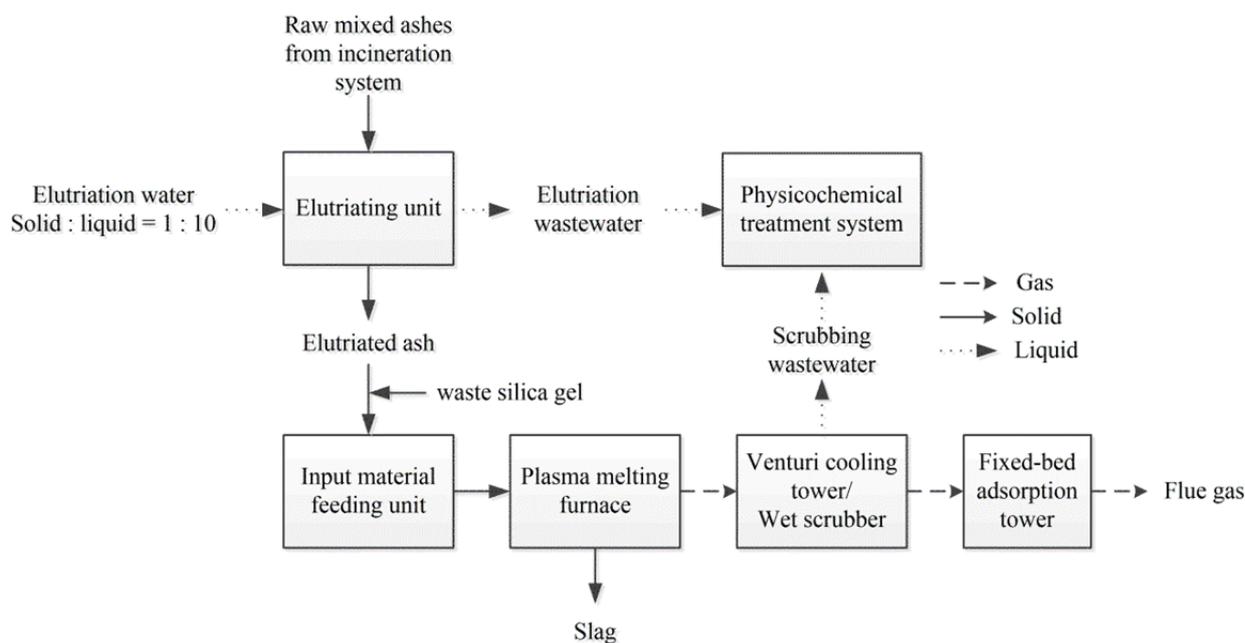


Fig. 1. Process flow diagram of plasma melting system.

including slag, solid phase in wastewater, particulate phase in flue gas, were collected, dried, ground, and digested for the further analysis. The metal concentration in wastewater and digests was measured using atomic absorption spectroscopy (AAS, Agilent technologies 50AA).

Analysis for PCDD/F and Metal Content

The elutriating wastewater and solid specimens were pretreated by a serial step: extraction with *n*-hexane, nitrogen-blowing concentration, cleanup and fractionation procedure, and nitrogen-blowing re-concentration for the PCDD/F analysis. The procedure for PCDD/F analysis was conducted following the procedure in a previous study (Wang and Chang-Chien, 2007) and the detail was given in Part 1. For metal content analysis, the solid specimens were all digested using concentrated acid following a digestion procedure which was modified from the standard method provided in NIEA R317.10C (TEPA, 2002). The pulverized specimens (~0.1 g) were added with a concentrated acid mixture composed of 3 mL HCl (hydrochloric acid, 32 wt%) and 3 mL HNO₃ (70 wt%), held and sealed in Teflon vessels. The Teflon vessels were heated using a microwave digester (MARS Xpress, CEM). The heating program was heated to 200°C at a rate of 6°C min⁻¹, isothermally held for 30 mins, and cooled to room temperature with forced ventilation. The digested solutions were diluted with deionized water to 50 mL, filtrated using mixed cellulose ester filters, and analyzed using AAS.

Analysis for Surface Characteristic and Metal Leaching Behavior

Solid specimens, including raw mixed ashes, elutriated ashes, and slag, were examined using scanning electron microscopy-energy dispersive spectroscopy (SEM-EDS, JEOL JXA-840). The solid specimens were initially pulverized to powder and screened by a mesh 200 sieve to ensure that the diameter of powder was smaller than 74 µm. The powdery specimens were then adhered using twin

adhesive to a copper plate. This plate was coated with Au film using ion coating sputtering to maintain its electric conduction. The specimens were then examined by SEM-EDS with a magnification factor of 10,000 folds and an accelerating voltage of 25 kV to evaluate their surface characteristics.

In addition, the metal mobility of slag powder was evaluated using toxicity characteristic leaching procedure (TCLP). An acid solution (pH = 4.93 ± 0.05) was prepared by a procedure: 5.7 mL glacial acetic acid was added with 500 mL deionized water and 64.3 mL NaOH solution (1 N) and diluted with deionized water to 1000 mL. The slag and acid solution were mixed with a mass ratio of liquid:solid = 20:1. The mixture was shaken overhead at 30 turn min⁻¹ for 18 hrs. The leachate was digested, filtered and analyzed using AAS. The detail procedure, including solution preparation, leaching conditions, dilution, digestion, and filtration, all followed the standard method stated in TEPA (2003a).

RESULTS AND DISCUSSION

Pollutant Characteristics of Input-materials

The composition and concentration of materials during the elutriating process was shown in Table 1. The raw mixed ashes had extremely high level of Na (175,000 mg kg⁻¹), Cl (182,000 mg kg⁻¹) and PCDD/Fs (13.3 ng I-TEQs g⁻¹). The NaCl came from the reaction of HCl existing in the flue gas and the injecting alkaline solution (40% NaOH) in the first and secondary quenching towers of the incineration system. The PCDD/F level in raw mixed ashes was about 10 times higher than that of general solid waste incinerator (Tu et al., 2011). The PCDD/Fs were generated during the incineration process of laboratory waste due to high Cl level of input-materials (Hatanaka et al., 2005, Chin et al., 2012). The raw mixed ashes also had heavy metals, such as Cr (18,600 mg kg⁻¹), Fe (45,100 mg kg⁻¹), and Ni (6,810 mg kg⁻¹). After the elutriating process, the

Table 1. Composition and concentration of materials during elutriating process (n = 3).

	Raw mixed ashes (mg kg ⁻¹), RSD(%)	Elutriated ashes (mg kg ⁻¹), RSD(%)	Elutriating wastewater (mg L ⁻¹), RSD(%)	Washout ratio (%)
Al	476, 18.5	461, 15.4	16.0, 8.57	40.5
Ca	5,780, 23.4	1,270, 16.6	425, 34.8	77.7
Cd	19.7, 15.6	9.98, 23.8	1.65, 16.1	76.5
Cr	18,600, 11.4	18,000, 8.21	212, 7.83	18.8
Co	239, 8.55	123, 7.73	205, 12.6	97.1
Cu	604, 6.78	464, 12.6	45.8, 9.12	66.0
Fe	45,100, 13.5	34,600, 13.3	1,210, 8.33	22.7
Mg	601, 16.6	330, 7.95	41.3, 16.4	71.1
Mn	830, 21.1	247, 8.86	69.2, 30.5	84.6
Na	175,000, 9.74	6,040, 11.7	18,100, 18.3	98.2
Ni	6,810, 6.25	1,070, 15.3	490, 23.4	90.0
Pb	342, 10.8	365, 12.7	18.0, 15.1	49.2
Zn	1,360, 12.1	142, 22.4	59.8, 17.3	89.2
Cl	182,000, 13.3	23,600, 12.7	84,600, 14.1	93.4
Total PCDD/F content	157 ng g ⁻¹ , 14.3	234 ng g ⁻¹ , 17.1	37.6 pg L ⁻¹ , 12.4	0.3
PCDD/F content in I-TEQs	13.3 ng g ⁻¹ , 10.8	20.3 ng g ⁻¹ , 12.4	2.19 pg L ⁻¹ , 9.25	0.2

mass reduction was 45.5% due to >90% NaCl being dissolved into the elutriating wastewater and, thus, the major species in the elutriating wastewater were Na (18,100 mg L⁻¹) and Cl (17,000 mg L⁻¹). In addition, significant fraction of metals was washed out from the raw mixed ashes resulting that the metal level of elutriated ashes was reduced simultaneously. On the contrary, the PCDD/F level of elutriated ashes was elevated from 13.3 to 20.3 ng g⁻¹ which roughly doubled that of raw mixed ashes before the elutriation process. This can be explained by that only trace amount of PCDD/Fs was washed out (<0.5%) and mass reduction caused the enrichment of PCDD/Fs in the elutriated ashes.

Table 2 shows the composition and mass contribution of input-materials, including elutriated ashes and waste silica gel. The waste silica gel, mainly composed of SiO₂, had 13,600 mg kg⁻¹ of Cl and trace amount of hazardous metals (<100 mg kg⁻¹) and PCDD/Fs (0.091 ng I-TEQ g⁻¹). Therefore, the PCDD/Fs, metals, and Cl of the input-materials during the plasma melting process were mainly contributed by elutriated ashes.

Pollutant Characteristics of Output Materials

Table 3 shows the composition and concentration of output materials. The slag was mainly composed of Ca (89,900 mg kg⁻¹), Fe (31,300 mg kg⁻¹), and Na (52,100 mg kg⁻¹) and the content of heavy metals (Cd, Cr, Cu, Mn, Ni, Pb, and Zn) and Cl were all lower than 10,000 mg kg⁻¹. The PCDD/F level of slag was reduced to 0.011 ng I-TEQ g⁻¹ which was only 0.05% to the PCDD/F level of elutriated ashes. The PCDD/F profile of the specimens before and after plasma melting process was shown in Fig. 2. For the elutriated ashes, the PCDD/F mass mainly resided in 1,2,3,4,6,7,8-HpCDF (25.2%), and distributed uniformly in 2,3,4,7,8-PeCDF (8.1%), 1,2,3,4,7,8-HxCDF (9.6%), 1,2,3,6,7,8-HxCDF (11.0%) and 2,3,4,6,7,8-HxCDF (9.8%). After the plasma melting process, the PCDD/F profile of

slag was completely different with that of elutriated ashes. The PCDD/F mass of slag mainly distributed in OCDD (61.7%) and OCDF (32.0%) which both were 8-Cl PCDD/F. The destruction efficiency (= (PCDD/F mass of melting materials/PCDD/F mass of slag) × 100%) of OCDD and OCDF was 75.1% and 91.9%. However, the destruction efficiency for other PCDD/F congeners were all higher than 99.0% and those for total and in I-TEQ PCDD/Fs were up to 97.65% and 99.95%. The PCDD/F destruction efficiency shows that 8-Cl PCDD/Fs was relatively stable in the high temperature environment.

In the scrubbing wastewater, the major composition in water phase was Na (24,400 mg L⁻¹) and Cl (16,700 mg L⁻¹) and other metal species and PCDD/Fs were in trace amounts. The composition of solid phase was Ca (251,000 mg kg⁻¹), Pb (95,700 mg kg⁻¹), and Zn (53,000 mg kg⁻¹).

There is not any regulated emission standard for plasma melting furnace and thus that for solid waste incinerator was used to evaluate its performance (TEPA, 2003b, 2005). The concentration of Cd, Pb, and PCDD/Fs in the flue gas was n.d., 0.19, and 0.007 ng I-TEQ Nm⁻³, respectively, and all of them were much lower than the regulated emission standards. The mass distribution of pollutants among the output materials was shown in Fig. 3. The water phase and solid phase were merged into scrubbing wastewater and the gas phase and particulate phase were merged into flue gas. The metal species which have high boiling points, such as Al (94.8%), Ca (97.6%), Cr (95.0%), Cu (73.1%), Fe (99.3%) Mg (91.1%), Mn (98.8%), and Ni (96.6%) mainly stayed in the slag. On the contrary, Cd (99.9%), Pb (70.5%), and Zn (68.9%), with low boiling points, mainly vaporized into the flue gas, removed by the scrubber, and existed in the scrubbing wastewater. 99.6% of Cl vaporized into the flue gas and dissolved into scrubbing wastewater. The metal distribution was governed by boiling points and density which was similar to that in a previous study (Kuo et al., 2004). In addition, the metal removal efficiencies of

Table 2. Level and contribution of PCDD/Fs, Cl, and metals of input-materials (n = 3).

Item	Level		Mass distribution (%)	
	Elutriated ashes (mg L ⁻¹), RSD(%)	Waste silica gel (mg L ⁻¹), RSD(%)	Elutriated ashes	Waste silica gel
Al	461, 15.2	5.37, 6.7	99.5	0.5
Ca	1,270, 8.9	9.49, 4.8	99.7	0.3
Cd	9.98, 13.4	25.3, 20.5	49.7	50.3
Cr	18,100, 7.6	0.002, 23.1	100.0	0.0
Co	123, 12.1	5.41, 15.3	98.3	1.7
Cu	464, 15.8	0.12, 24.4	100.0	0.0
Fe	34,590, 18.6	0.067, 22.8	100.0	0.0
Mg	330, 19.4	7.64, 18.7	99.1	0.9
Mn	247, 21.1	0.0507, 21.4	100.0	0.0
Na	6,040, 27.4	39.4, 27.1	99.7	0.3
Ni	1,070, 19.8	0, 29.3	100.0	0.0
Pb	365, 17.7	19.9, 23.7	97.9	2.1
Zn	142, 22.5	2.24, 20.8	99.4	0.6
Cl	23600, 23.6.	13600, 16.6	81.3	18.7
Total PCDD/F level	234	1.28	99.8	0.2
PCDD/F level in TEQs	20.3	0.091	99.8	0.2

Table 3. Composition or concentration of output materials (n = 3).

Item	Scrubbing wastewater				Flue gas			
	Slag (mg kg ⁻¹), RSD(%)	Water phase (mg L ⁻¹), RSD(%)	Solid phase (mg kg ⁻¹), RSD(%)	Gas phase (mg Nm ⁻³), RSD(%)	Particulate phase (mg Nm ⁻³), RSD(%)	Regulated emission standard	Efficiency of APCDs (%)	
Al	4,820, 5.8	3.51, 6.5	13,900, 5.9	910, 17.7	8,190, 20.1	N.R.	92.31	
Ca	89,900, 12.4	33.8, 11.3	251,000, 11.7	0.62, 3.9	11.7, 15.1	N.R.	99.87	
Cd	0.0198, 13.6	0.534, 18.8	55.6, 16.5	N.D.	N.D.	0.04	> 99.99	
Co	58.1, 21.3	2.41, 14.1	289, 15.2	0.01, 12.3	0.04, 22.6	N.R.	99.99	
Cr	3,550, 15.8	2.97, 16.4	19300, 19.5	0.19, 8.6	0.73, 11.6	N.R.	99.89	
Cu	3,870, 14.2	29.5, 15.6	25.8, 20.7	0.05, 9.1	0.1, 8.1	N.R.	> 99.99	
Fe	31,300, 22.1	2.41, 11.5	40,600, 18.4	0.87, 12.7	6.41, 23.3	N.R.	99.21	
Mg	6,800, 6.9	13.1, 5.7	14,400, 23.4	0.14, 22.3	1.14, 16.6	N.R.	99.96	
Mn	1,520, 12.3	0.306, 9.5	1,300, 30.3	0.03, 15.4	0.14, 25.5	N.R.	99.78	
Na	52,100, 11.9	24,400, 10.4	39,100, 17.7	14.4, 28.3	19.9, 18.8	N.R.	99.99	
Ni	2,110, 16.4	1.38, 12.7	3,170, 4.9	0.11, 32.3	0.36, 26.2	N.R.	99.86	
Pb	206, 13.3	5.76, 8.8	95,700, 15.9	0.02, 40.1	0.17, 30.1	0.5	99.99	
Zn	520, 18.7	21.3, 6.3	53,000, 6.7	0.1, 19.8	0.73, 3.7	N.R.	99.98	
Cl	2,800, 20.5	16,700, 23.3	21,500, 20.1	N.D.	15.5, 13.3	N.R.	> 99.99	
Total PCDD level	5.48 ng I-TEQ g ⁻¹ , 11.6	10.4 pg L ⁻¹ , 14.7	17.2 ng I-TEQ g ⁻¹ , 14.2	0.01 µg Nm ⁻³ , 25.5	0.03 µg Nm ⁻³ , 21.1	N.R.	98.28	
PCDD/F level in I-TEQs	0.011 ng I-TEQ g ⁻¹ , 19.3	0.53 pg L ⁻¹ , 15.8	0.25 ng I-TEQ g ⁻¹ , 12.1	0.002 µg Nm ⁻³ , 15.3	0.005 µg Nm ⁻³ , 16.6	0.5 µg Nm ⁻³	95.51	

N.D.: non-detectable; N.R.: non-regulated.

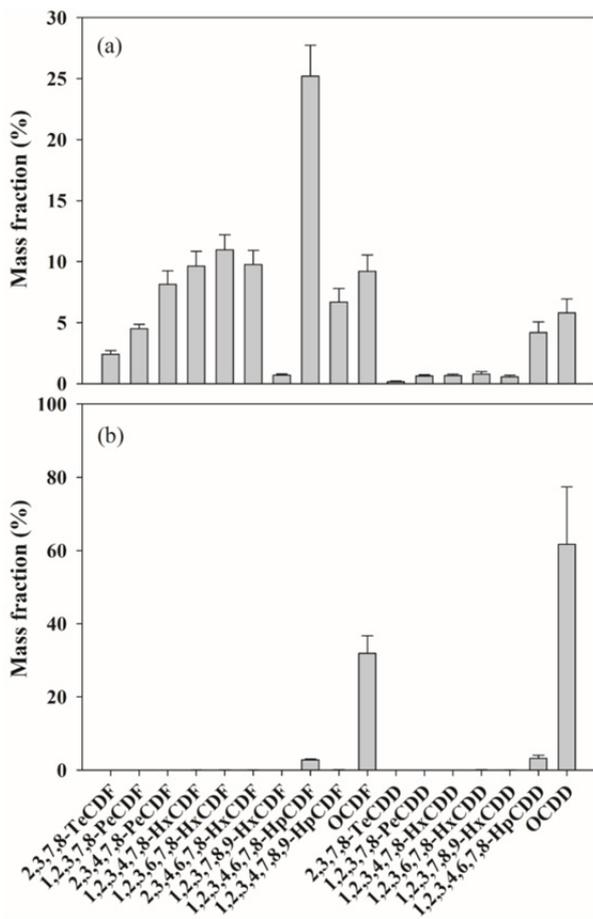


Fig. 2. PCDDF profile of elutriated ashes and slag: (a) elutriated ashes; (b) slag.

APCDs were all higher than 90%. The O/I ratios of total and in TEQs PCDD/Fs were 0.000444 and 0.000188, indicating the plasma melting process has good performance on the decomposition of PCDD/Fs. In addition, the total and in I-TEQ PCDD/F removal efficiency of APCDs was 98.28 and 95.51. Therefore, < 1% PCDD/Fs was discharged from the flue gas, indicating that this process has little impact on the atmosphere.

Fig. 4 shows the PCDD/F profiles for gas phase and particulate phase of the flue gas. For the gas phase, the PCDD/F mass roughly distributed in 2,3,7,8-TeCDF (13.1%), 1,2,3,7,8-PeCDF (11.8%), 2,3,4,7,8-PeCDF (15.8%), 1,2,3,4,7,8-HxCDF (8.50%), 1,2,3,6,7,8-HxCDF (10.7%), 2,3,4,6,7,8-HxCDF (8.95%), and 1,2,3,4,6,7,8-HpCDF (15.8%) and the fractions of other congeners were all < 3%. The PCDD/F profile of particulate phase was similar to that of elutriated ashes, indicating that the particulate phase came from vaporization of molten materials during the plasma melting process.

Surface Characteristics of Solid Specimens

Fig. 5 shows the SEM images of solid specimens, including raw mixed ashes, elutriated ashes and slag. The raw mixed ashes had bulky structure and powdery agglomerate on its surface and the powdery agglomerate was NaCl according to the observation in our previous study (Liao et al., 2014). During the elutriating process, most NaCl was washed out and the amount of powdery agglomerate on the surface obviously decreased. After the plasma melting process, the elutriated ashes were transformed into glassy amorphous slag. The TCLP was conducted to evaluate the metal mobility in slag. The leaching result

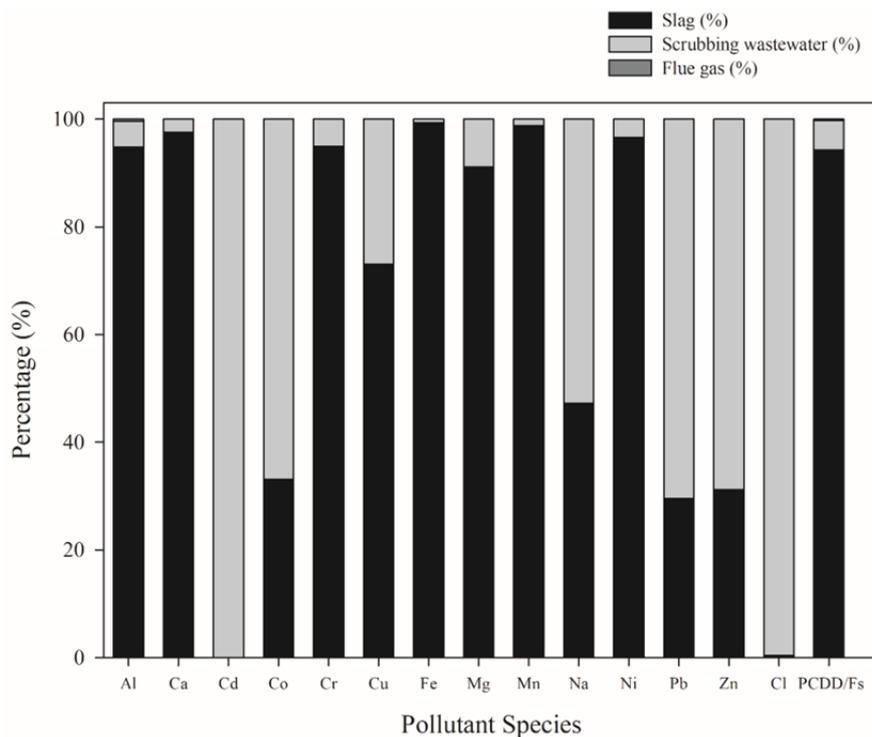


Fig. 3. Mass distribution of pollutant species among output materials.

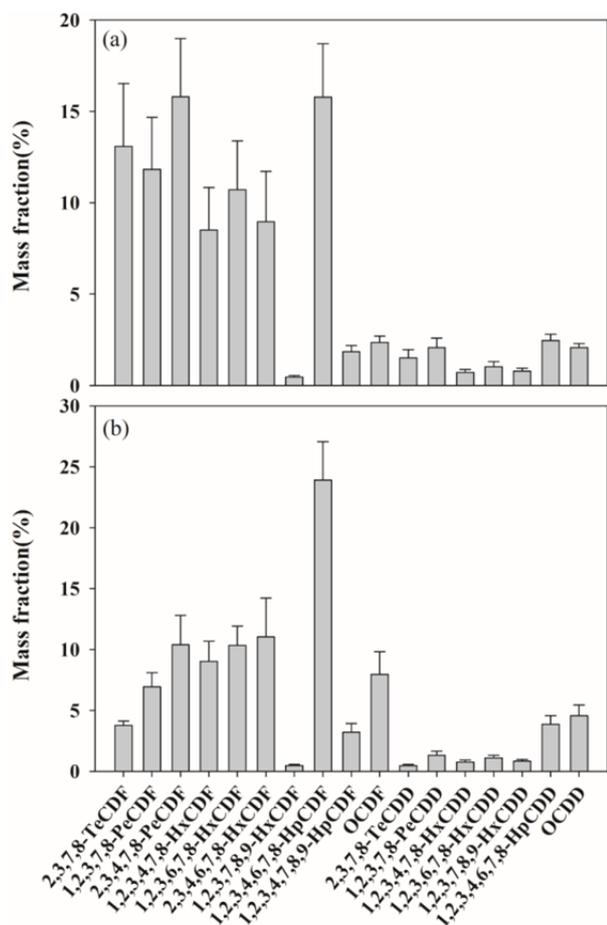


Fig. 4. PCDD/F profile of flue gas: (a) particulate phase; (b) gas phase.

shows that there is not any hazardous metal detected, indicating the slag could be regarded as a non-hazardous product (TEPA, 2012) and recycled as building materials or road pavement (Lubeck *et al.*, 2012).

Comparison of Operation Characteristics between Two Thermal Systems

Table 4 compared the operation characteristics of the plasma melting system with the incineration system (in Part 1). The capacity of incineration system (375 kg hr^{-1}) is three times as much as that of plasma melting system (125 kg hr^{-1}). For the incineration system, the elutriated ashes were co-incinerated with laboratory waste with a mixing ratio of elutriated ashes:laboratory = 0.05. Therefore, the treatment capacity is 18.8 kg hr^{-1} which is only 20% of that in the plasma melting system. The PCDD/F levels of fly ashes ($5\text{--}20 \text{ ng I-TEQ g}^{-1}$) and bottom ash ($0.4 \text{ ng I-TEQ g}^{-1}$) generated during the incineration process were much higher than that in the plasma melting system ($0.25 \text{ ng I-TEQ g}^{-1}$ PCDD/Fs). In addition, heavy metals were not immobilized in incinerator fly ashes and bottom ash, and, thus, these ashes needed further treatment for final disposal.

The major by-product of plasma melting system is scrubbing wastewater (about 100 L hr^{-1}) and slag ($0.011 \text{ ng I-TEQ g}^{-1}$ PCDD/Fs). The scrubbing wastewater was

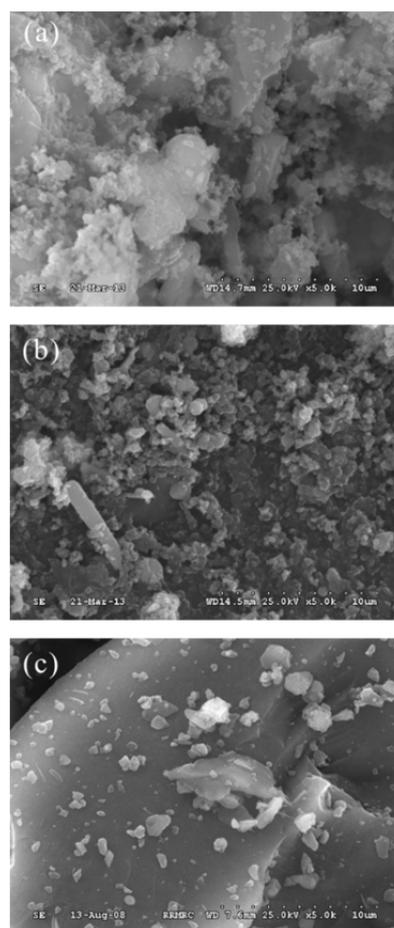


Fig. 5. SEM images of solid specimens: (a) raw mixed ashes, (b) elutriated ashes, and (c) slag.

treated by the physicochemical treatment system and the slag can be directly recycled as composite or building material (Bucher *et al.*, 2017). The operation temperatures of incineration system and plasma melting system were $800\text{--}900^\circ\text{C}$ and $> 1450^\circ\text{C}$, respectively. The different operation temperatures made the variation of the decomposition of PCDD/Fs. The O/I ratios for total amount and in I-TEQ PCDD/Fs were 0.49 and 0.348 in the incineration system but they were 0.000444 and 0.000188 in the plasma melting system. The high operation temperature had superior PCDD/F decomposition performance but consumed much more energy at the same time. Due to the high energy consumption of plasma melting system, the operation cost is $\sim 750 \text{ USD ton}^{-1}$ which is five times as much as that of incinerator (Ecke *et al.*, 2000). The comparison results show that the plasma melting system has excellent performance to treat elutriated ashes but the high operation cost and energy consumption is its inevitable drawback.

CONCLUSIONS

This study investigated the performance of a plasma melting system in treating elutriated ashes and compared the result with that in Part 1. The raw mixed ashes were mainly composed of Na ($175,000 \text{ mg kg}^{-1}$) and Cl ($182,000 \text{ mg kg}^{-1}$)

Table 4. Comparison of operation characteristics between incineration system and plasma melting system.

	Incineration system	Plasma melting system
Capacity	375 kg hr ⁻¹ (containing 18.8 kg hr ⁻¹ of elutriated ashes)	125 kg hr ⁻¹ (containing 89.3 kg hr ⁻¹ of elutriated ashes)
Treatment style	Co-incineration with laboratory waste	Melting with waste silica gel
Treatment temperature	800–900°C	> 1400°C
Effect on stabilization of heavy metals	No effect	Excellent effect on the immobilization of heavy metals (much below the regulated standard of TCLP)
Byproduct	Fly ashes and bottom ash (containing 5–20 and 0.4 ng I-TEQ g ⁻¹ PCDD/Fs)	Fly ash and slag (containing 0.25 ng I-TEQ g ⁻¹ PCDD/Fs)
O/I ratio of total PCDD/Fs (in I-TEQs)	0.49 (0.348)	0.000444 (0.000188)
Operation cost USD ton ⁻¹	150	750

and contained PCDD/Fs (13.3 ng I-TEQs g⁻¹) and heavy metals, such as Cr (18,600 mg kg⁻¹), Fe (45,100 mg kg⁻¹), and Ni (6,810 mg kg⁻¹). The elutriating process washed out most of the NaCl and thus caused the concentration of PCDD/Fs to increase from 13.3 to 20.3 ng I-TEQs g⁻¹. Using the plasma melting system, the elutriated ashes were transformed into slag, which was mainly composed of Ca (89,900 mg kg⁻¹), Fe (31,300 mg kg⁻¹), and Na (52,100 mg kg⁻¹) and had trace amount of PCDD/Fs (0.011 ng I-TEQ g⁻¹). The metal species with high boiling points, including Al, Ca, Cr, Cu, Fe, Mg, Mn, and Ni, primarily remained in the slag. The metals with low boiling points, including Cd, Pb, and Zn, were mainly vaporized into flue gas and removed by the scrubber. The slag has a glassy amorphous structure, which immobilizes heavy metals, and there were no metals detected using TCLP. A comparison of operating characteristics between the incineration system and the plasma melting system shows that the latter requires higher costs and energy. However, the plasma melting system has a large capacity (89.3 kg hr⁻¹) for treating elutriated ashes and exhibits excellent performance in terms of PCDD/F decomposition (O/I ratio = 0.000188). In addition, the slag can be directly recycled due to its stability. Therefore, overall, the plasma melting system is a preferable method for treating elutriated ashes from incinerated laboratory waste.

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