Korean J. Chem. Eng., **29**(5), 627-635 (2012)
DOI: 10.1007/s11814-011-0229-8

Evaluation of heavy metal distribution and biological toxicity in agglomeration bed material during artificial waste incineration in fluidized bed

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(*Received 1 November 2010 • accepted 30 August 2011*)

Abstract−This study discusses the impact of different operating parameters on the bed material particle size and heavy metal distribution, and evaluates the impact of bed material heavy metal on the environment through TCLP and *Vibrio fischeri* test. The experimental results show that the bed material particle size distribution inclines to smaller particle sizes as the operating temperature increases. When there is Na, the particle size increases due to the agglomeration of eutectic. As for the heavy metal distribution, the combination of the fine particle sizes (<0.59 mm) with a large surface area and the large particle sizes with multiple eutectics has a higher heavy metal concentration. According to the results of leaching concentration of bed materials with different particle sizes, the heavy metals with large (>0.84 mm) and fine (<0.59 mm) particle sizes have the maximum leaching concentration. As for the biological toxicity, when the temperature is 700 °C or Na concentration is 0.3%, the biological toxicity is at its maximum, which may due to a high accumulation of heavy metals.

Key words: Agglomeration, Fluidized Bed, Heavy Metal, TCLP, Biological Toxicity

INTRODUCTION

In the operation process of a fluidized bed incinerator, the bed material agglomeration always puzzles engineers. The bed material agglomeration may affect the fluidization parameters, such as the minimum fluidization velocity, bubble size, frequency, and rising velocity, even to the extent of shutting down the fluidized bed (defluidization) [1,2]. As for the waste incineration treatment, because the composition of waste is quite complicated, it may contain some substances that may be viscous, such as the alkaline metals and alkaline earth metals compounds [3,4], and these substances are the major factors causing the defluidization of the fluidized beds. Gluckman et al. [5] and Skrifvars et al. [6] pointed out that the agglomeration of bed material depends on the viscosity of the bed material and the collisions between particles. Previous studies also found that the liquid eutectic materials derived from the alkali metal elements at high temperature are likely to adhere to the bed material surface, so that the bed material becomes viscous and results in the agglomeration/defluidization [7,8].

The incineration process may generate pollutants, such as the organic pollutants (PAHs and BTEXs), heavy metals and acidic gases [9]. The generation of pollutants is influenced by many operating factors. Thus, the fluidization quality in the incineration process would influence the generation of pollutants directly. The major factors in the incineration operating conditions that influence the heavy metal distribution are: (1) composition of waste, (2) combustion temperature, (3) operating gas flow rate, (4) feed load, and (5) waste gas treatment equipments. Fournier et al. [10] indicated that the distribution of heavy metals is related to the characteristics of heavy metals, their compounds, as well as their boiling points. In addition, Hiraoka and Takeda [11] and Gerstle and Albrinck [12] pointed out that the combustion temperature would influence the distribution ratio of heavy metals in the bottom ash, where the rise of temperature would reduce the amount of zinc, lead, and cadmium in the bottom ash, while the content of arsenic, cadmium, mercury, zinc, and lead in the exhaust gas would increase. Therefore, the distribution of heavy metals in the incineration system is related to both the characteristics of heavy metals and the incineration operating conditions.

It is necessary to determine whether the bottom ash and fly ash derived from the incinerated waste are harmful to the environment, and many countries employ the toxicity characteristic leaching procedure (TCLP) in the determination of hazardous materials. If the leached heavy metal concentration exceeds the regulatory standards, it is regarded as a hazardous waste, and the waste should be further treated to reduce the hazards of possible leaching of heavy metals from the bottom ash being released into the environment. Previous studies applied the toxicity leaching test to analyze the incinerated fly ash, bottom ash, or reused substances to verify whether the treating process is effective in make the hazardous materials harmless and to increase the feasibility of reuse and reclamation [13-16]. Furthermore, the biological toxicity test Microtox (Vibrio fischeri-EC50%) is a biological toxicity testing method [17], where it can detect the toxicity of heavy metals and organic pollutants in living organisms during a short period of time. Previous studies also used it to test the toxicity of heavy metals in the liquid extracted from the coal ash on the environment and living organisms [17,18].

In the fluidized bed incineration process, the agglomeration will affect the heavy metal adsorption and stability in bed particles, and it also influences the leaching concentration and environmental toxicity. These phenomena will affect the disposal and treatment of bottom ash. However, few studies have discussed the impact of the agglomeration/defluidization in the incineration process on the heavy metal distribution and toxicity in the bed material. Therefore, this

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study aims to discuss the effect of different fluidized bed operating parameters on the bed material heavy metal distribution, and the influence of heavy metals in the bed material on the environmental toxicity. Real municipal solid waste will contain many kinds of heavy metals, such as Cd, Pb, Cr, Fe, Al, Zn, Cu and so on. However, in order to simplify the experimental condition, some important heavy metals with high biological toxicity will be selected. So, in this study, three heavy metals Cd, Pb, and Cr are of high, medium and low volatile metals, with boiling points of 765 ºC, 1,740 ºC and 2,672 ºC separately, are selected to simulate the heavy metal in waste.

To simplify the experimental impact factors, the agglomeration is simulated by preparing different artificial wastes. The influence of different operating gas velocities, alkali metal contents and operating temperatures on the heavy metal distribution is discussed, and the bed materials with different particle sizes are sampled to test their heavy metal leaching concentration and biological toxicity. This study continued the previous experiments of Liu et al. [19], who took partial bed material samples from the test process for further analysis. The possible leaching quantity of heavy metals can be obtained from the agglomerated materials through TCLP. The biological toxicity test investigates their potential harm to organisms in the environment, so as to determine the characteristics of agglomerated materials as a reference for the fluidized bed incinerator operation and subsequent bed material treatments.

EXPERIMENTAL METHOD

1. Apparatus

Fig. 1 shows a laboratory-scale fluidized bed incinerator; the main reactor is a stainless steel tube with inside diameter of 9 cm, and height of 1.2 m. The furnace bottom is a stainless steel porous plate, and the open area is 15.2%. There is an electrical heating system outside the stainless steel tube that is covered by ceramic fiber for heat insulation and fixed by a stainless steel shell. The temperature is controlled by a temperature feedback control system and a thermocouple systematically. A cyclone collector at the gas outlet is connected with a series of active carbon filter to collect the fly ash.

2. Preparation of Artificial Wastes

To simulate the generation of agglomeration/defluidization in the incineration process, the Na element is added in the simulated waste to form a low-melting eutectic substance, so that its influence on the agglomeration and the emission of heavy metals can be observed. The bed material used in the experiment is silica sand, the bed material particle size is 770 μm, and the density is 2,600 kg/m^3. The minimum fluidization velocity is measured before the experiment, and the method is as indicated in Lin et al. [20]. The heavy metals in the waste are simulated by adding nitrate metals in the simulated waste. The simulated waste is composed of sawdust (1.6 g) and polypropylene (PP) (0.35 g), where the sawdust and PP are added with 1 mL nitrate heavy metal water solution and covered by a polyethylene (PE) bag (0.29 g). Before experiment, the elemental analysis of sawdust, polypropylene and polyethylene were detected by elemental analyzer (EA). These results of elemental analysis can be used to calculate the stoichiometry air. Table 1 shows the results of elemental analysis. Each pack of simulated waste weighs 3.24 g, and the excessive air is controlled at 40% (62 L/min) in the combustion process. The operating temperature is 700, 800, and 900 ºC, respectively. The concentration of the Na element is 0.3, 0.7, and 1.1%, respectively, and the concentrations of the Ca and Mg of the alkaline earth elements are both 0.7%. The operating conditions are shown in Table 2.

3. Experimental Procedure

The experimental procedure is that when the sand bed is heated to the preset temperature and stabilized, the blower is switched on to feed air. The flow is regulated through the flow meter, and increases the air temperature by preheating the chamber to avoid cold air entering the sand bed causing a large temperature fluctuation. The simulated waste enters the combustion chamber for incineration through the feed inlet, and the feeding rate is 1 pack/20 sec. In the experiment, the agglomeration should be observed, and the pres-

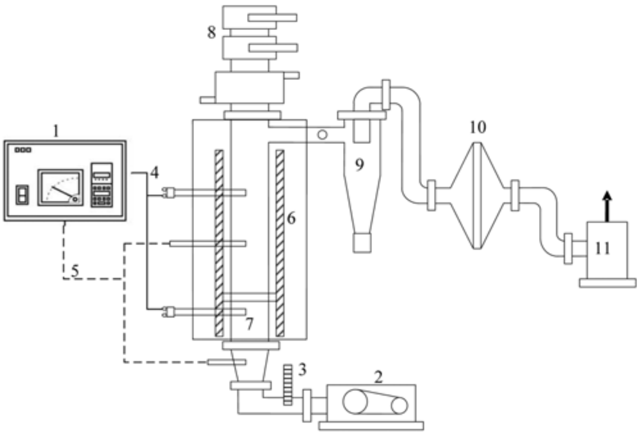

Fig. 1. The bubble fluidized bed incinerator.

1. PID controller	7. Sand bed
2. Blower	8. Feeder
3. Flow meter	9. Cyclone
4. Thermocouple	10. Filter
5. Pressure transducer	11. Induced fan
6. Electric resistance	

Table 1. Elemental analysis of different wastes by weight

	C (%)	H (%)	O (%)	N (%)
Sawdust	43.12	5.80	46.07	5.01
Polyethylene (PE)	85.71	13.04	0.39	0.86
Polypropylene (PP)	86.16	12.20	0.52	1.12

Table 2. Operating conditions for the experiments

Run	Temperature (ºC)	Species of heavy metal	Concentration (%)		
			Na	Ca	Mg
1	800	Pb, Cr, Cd	---	---	---
2	800	Pb, Cr, Cd	0.3	---	---
3	800	Pb, Cr, Cd	0.7	---	---
4	800	Pb, Cr, Cd	1.1	---	---
5	700	Pb, Cr, Cd	0.7	---	---
6	800	Pb, Cr, Cd	0.7	---	---
7	900	Pb, Cr, Cd	0.7	---	---
8	800	Pb, Cr, Cd	0.7	0.7	---
9	800	Pb, Cr, Cd	0.7	---	0.7

sure change should be detected to determine the generation of agglomerates. The pressure is measured using two pressure probes to measure the pressure difference of the freeboard area of the sand bed, while the other end of the probe is connected to a diff-pressure transmitter of which the measurement range of the pressure difference is 0-1,000 mmH_2O. After the experiment is completed, the reactor is cooled to room temperature and the bed materials are taken out to analyze. To understand the interception of heavy metals with different bed material particle sizes, the agglomerated substances collected after the experiment were analyzed by ASTM standard sieve. The bed materials are divided into seven particle size intervals, including greater than 1.41 mm, 1.41-1 mm, 1-0.84 mm, 0.84-0.7 mm, 0.7-0.59 mm, 0.59-0.5 mm, and less than 0.5 mm, to learn about the bed material size distribution. Then, the bed materials of different particle sizes are sampled to analyze the concentrations of three heavy metals. When analyzing the concentration of heavy metal samples, the sieved solid samples are first pretreated by using the microwave digestion process. Then, the heavy metal concentrations are analyzed by inductively coupled plasma spectrometer (ICP).

4. Toxicity Characteristic Leaching Test and *Vibrio fischeri* Test

In addition, to evaluate the influence of heavy metals intercepted in the agglomerated substances by the agglomeration/defluidization procedure on the environment, the heavy metal toxicity analysis is carried out on the bed materials. However, some bed materials are too little to compare in the seven particle sizes at the same time, so all the test bed materials are classified into four different particle sizes of large (<1 mm), medium (1-0.7 mm), small (0.5-0.7 mm), and fine particle size (<0.5 mm) for heavy metal toxicity analysis. The industrial waste toxicity characteristic leaching test procedure (R201.14C) declared by Taiwan Environmental Protection Administration and the *Vibrio fischeri* test are used as the evaluation indexes. The heavy metal leaching standard stipulated by Taiwan Environmental Protection Administration is lead: 5 mg/L, cadmium: 1 mg/L, and chrome: 5 mg/L. The heavy metal leaching quantity and its toxicity to organisms in the environment are shown by TCLP in order to serve as a reference for subsequent treatments.

Vibrio fischeri test uses Luminescent bacteria, especially *Vibrio fischeri* (NRRL B-11177), to detect the toxicity in the environment samples. The luminescent bacteria used in this study were purchased from Germany DSMZ, DSM-No 7151. The fluid nutrient medium was prepared according to ISO11348-1 [21], and the pH was adjusted to 7±0.2 using 0.1 M NaOH and 0.1 M HCl before measuring the toxicity of the samples. The logarithmic phase bacteria were diluted to OD=0.003, and the sample liquid was added at the ratio of 1 : 1. The luminescence value and inhibiting value were detected at 0, 5, and 15 minutes. The light inhibiting rate was calculated as follows:

$$\text{Light inhibiting rate }(\%)=\frac{I_0*f_k-I_f}{I_0*f_k}\times 100\%$$

I_0: sample initial luminescence value
I_f: 5 and 15 minute luminescence values of sample
f_k: I_{cf}/I_{c0} luminescence value adjustment factor
(I_{cf}: control group 5 and 15 minute luminescence values; I_{c0}: control group initial luminescence value)

When measuring the biological toxicity, the EC_{50} value of 160 mg/L phenol is set as the standard for quality control, and the results must be close to the EC_{50} value in literatures (measured values of EC_{50} are about 13-26 mg/L in literatures).

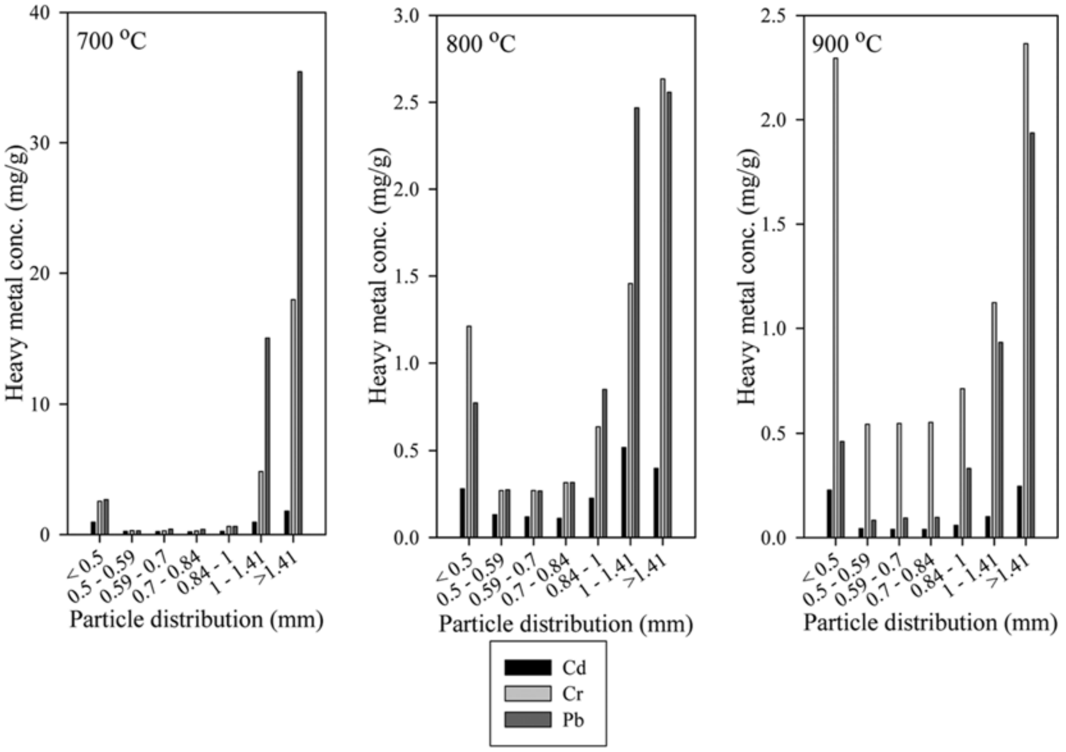

Fig. 2. Heavy metal distributions in sand bed for different operation temperature (0.7% Na).

RESULTS AND DISCUSSIONS

1. Influence of Operating Conditions on Bed Material Heavy Metal Distribution

1-1. Influence of Different Operating Temperatures on Bed Material Heavy Metal Distribution

Fig. 2 shows the concentration distribution of the bottom ash heavy metals in different particle sizes at different operating temperatures. Accordingly, the heavy metals in large and fine particle sizes have the maximum concentration at different operating temperatures. When the particle size was less than 0.59 mm, the heavy metal concentration in the bed material increased. When the bed material particle size was greater than 0.84 mm, the heavy metal concentration also increased.

With respect to different particle sizes, the bed material with fine particle sizes is derived from the attrition and thermal shock in the fluidization operating process [22-24], where the bed material surface area is large, and the bed is likely to adsorb heavy metals. Therefore, the more heavy metals are adsorbed by the smaller the bed material particle size. Hence, the smaller bed material heavy metal concentration increases. In consideration of the bed material in large particle sizes, the bed material with large particle sizes is formed because the low-melting eutectic materials produce the molten fluent materials in high-temperature operation, and its viscosity results in the agglomeration of the bed material; then, the bed material particle size is increased. Although the bed material with large particle size has a small surface area, the heavy metal concentration is still high, indicating that the heavy metals may not adhere to the bed material only through adsorption. Another factor may be that the heavy metals and Na produce a low-melting eutectic material, or when the eutectic material containing Na melts at high temperature and forms a fluent material, the feed-in heavy metals contact with it and adhere to or are covered by the eutectic fluent material. As a result, the heavy metal concentration in the bed material increases. It is observed from the SEM/EDS analysis of agglomerated bed materials (Fig. 3) that the agglomerated substances causing cementation between particles contain heavy metals Pb and Cr, which shows that the forming of low-melting eutectic material containing Na may stick or cover feed-in heavy metals.

When silica sand is used as the bed material, the silica sand can absorb a large amount of heavy metals in the incineration process [25], heavy metals Cd, Pb, and Cr are of high, medium and low volatile metals, the melting and boiling points are Cd melting point 321.18 °C and boiling point 765 °C; Pb melting point 327.6 °C and boiling point 1,740 °C; and Cr melting point 1,857 °C and boiling point 2,672 °C. Because the boiling points of Cr and Pb are higher than the operating temperature, the concentration of heavy metals Cr and Pb in the bed material is quite high. For different operating temperatures, when the operating temperatures increase, the concentrations of the three heavy metals in different bed materials decrease. Take the heavy metal Cd, for example; the heavy metal concentration in the bed material is at its minimum at 900 °C, secondly 800 °C and 700 °C. The experimental results show that the distribution of heavy metals coincides with the characteristics of heavy metal boiling points.

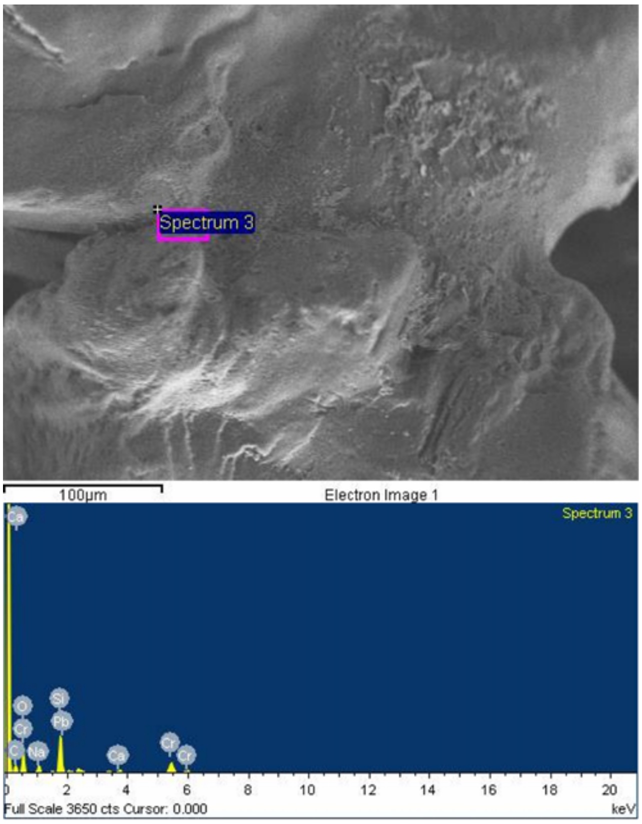

Fig. 3. The SEM/EDS analysis of the agglomerates.

1-2. Influence of Different Na Concentrations on Bed Material Heavy Metal Distribution

Fig. 4 shows the heavy metal concentration distribution in different bed material sizes at different Na concentrations. As seen, the heavy metal distribution trend is similar to the distribution trend in Fig. 2, where the bed materials with large and fine particle sizes have high heavy metal concentrations. From the analysis of different Na concentrations, the heavy metal concentration of all bed material sizes is at its maximum when the three heavy metals have 0.3% of Na. It seems that the bed material heavy metal concentration decreases as the Na concentration increases. This may be because when the Na concentration is low, it takes longer to accumulate Na to form agglomeration/defluidization, so that the feed rate and the accumulation of heavy metals are high, which causes the heavy metal concentration in bed materials of less than 0.59 mm and greater than 0.84 mm to increase greatly. The 0.59-0.84 mm bed material heavy metal concentration is higher than other operating conditions. For the Na addition in high concentrations, since the operation time is shorter, the heavy metal cumulant is lower; only the bed material with large particle size has a higher heavy metal concentration. Overall, the bed material heavy metal concentration distribution without the addition of Na is at its minimum, whereas when Na is added, the heavy metal concentrations in bed materials of different particle sizes tend to increase. Although the eutectic material formed by Na in the fluidization operating process would produce agglomerates and increase the risk of defluidization, the heavy metals and Na may produce a low-melting eutectic material or when the eutectic material containing Na melts at a high temperature and forms a fluent material, of which the feed-in heavy metals adhere to or are covered by the eutectic fluent material after contact, and causes the increase of the heavy metal concentration in bed material, and then

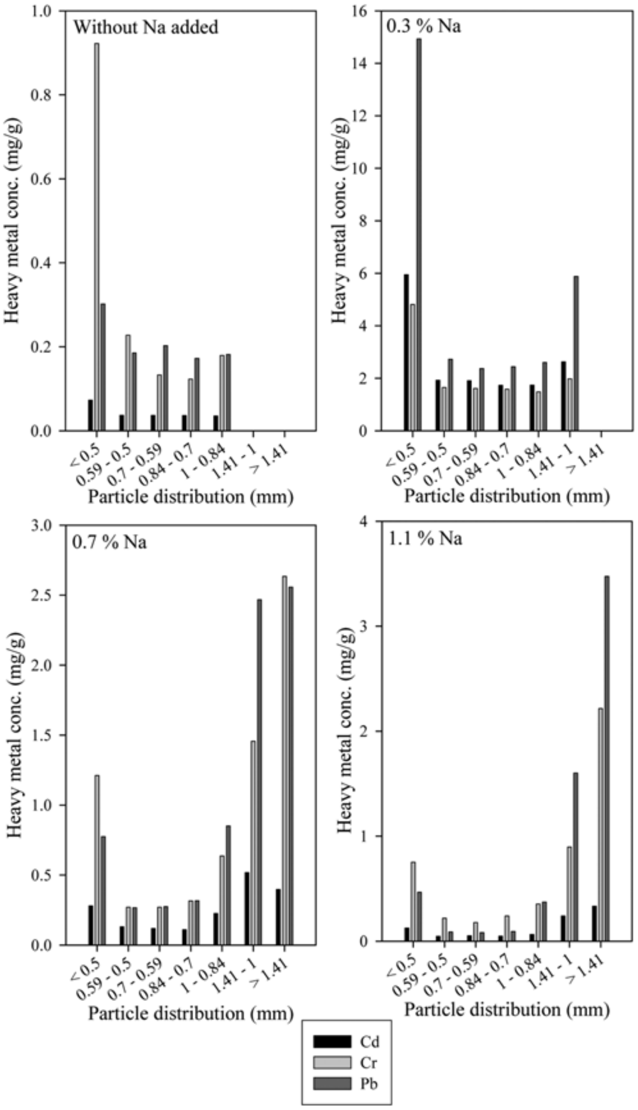

Fig. 4. Heavy metal distributions in sand bed for different Na concentrations (800 °C).

the heavy metal emission is reduced, while the agglomerated bed materials with large particle sizes have a higher heavy metal concentration.

1-3. Influence of Addition of Ca and Mg on bed Material Heavy Metal Distribution

Fig. 5 illustrates the distribution of heavy metal concentration in different particle sizes with and without Ca and Mg. After the addition of Ca and Mg, the heavy metal concentrations in bed materials of different grain sizes are higher than that without Na or with Na only. This may be because the addition of Ca and Mg prolongs the fluidization operating time, so the heavy metal feed rate increases, and the bed material absorbs more heavy metals while the large agglomerated grains accumulate a higher heavy metal concentration. Therefore, the addition of Ca and Mg helps to extend the fluidization operation, and slow down the agglomeration/defluidization, and also enables the bed material to intercept more heavy metals to reduce the emission of heavy metals.

According to Fig. 5, the addition of Ca and Mg prolongs the fluidization operating time, so the heavy metal feed rate increases, and the bed material absorbs more heavy metals. Therefore, heavy metals concentration of adding Ca increase in the fine particles. Comparing the addition of Mg, the smallest particle (<0.5 mm) doesn't seem to have this trend. However, the heavy metal concentration of other small particles (0.70-0.59 mm and 0.59-0.50 mm) still has higher concentration than those of only Na addition.

2. The Leaching Concentration Distribution of Bed Material Under Different Operating Conditions

2-1. Bed Material Heavy Metal Leaching Under Different Operating Temperatures

Fig. 6 shows the leaching concentration of heavy metals Cd, Cr, and Pb in different bed material grain sizes under different operating temperatures by TCLP. According to the results, the heavy metals in bed material with large particle sizes and fine particle sizes have the maximum leaching concentration in most of test processes, whereas the medium particles and fine particles have a low leaching quantity, especially Cr, due to the high boiling point of Cr, a large amount of it are intercepted in the bed material. Hence, its leaching quantity is the maximum among three metals. By comparing the heavy metal leaching results with the specified values of the Environmental Protection Administration, it is found that the leaching concentrations of Cd and Cr exceed the specified values, only the leaching quantity of Pb is below the specified value. Comparison of the heavy metal concentrations of different bed materials also shows that the heavy metal concentration difference between Pb and Cr that are intercepted in the bed material is small. However, the leaching concentrations show a large difference;, it may be due to the different bonding degrees of the three metals when the bed material forming agglomeration. Pb has a low leaching concentration maybe because the eutectic materials produced by Na at high temperature are unlikely to leach. For different operating temperatures, the leaching concentrations of the three metals have different trends. Since Cd is a volatile metal, most Cd is volatilized into the gaseous state when the system operation is at 900 °C. A few of them are intercepted in the bed material, so the bed material operated at 900 °C has the minimum leaching quantity of Cd. As Cr has the highest boiling point, most of Cr is intercepted in the bed material. However, the Cr compounds have high boiling points, so the temperature range of 700-900 °C has little influence. The Pb sample operated at 900 °C has the maximum leaching quantity, indicating that if the operating temperature is high, the Pb compound formed in the sand bed may be unstable.

2-2. Bed Material Heavy Metal Leaching at Different Na Concentrations

Fig. 7 illustrates the leaching concentrations of Cd, Cr, and Pb of TCLP at different Na concentrations. Based on the results, the leaching concentration of Cr is still the maximum, followed by Cd. Both of the concentrations exceed the specified value, only the leaching concentration of Pb coincides with the specified value. The heavy metals in bed materials of large and fine particles have the maximum leaching concentrations in most test processes, and medium and fine particles have small leaching quantity, especially for heavy metals Cd and Cr. By comparing the effects of different Na concentrations, when 0.3% Na is added, Cd and Cr have high concentration, and their distribution decreases as the Na concentration increases. This may be because the higher the Na concentration, the shorter

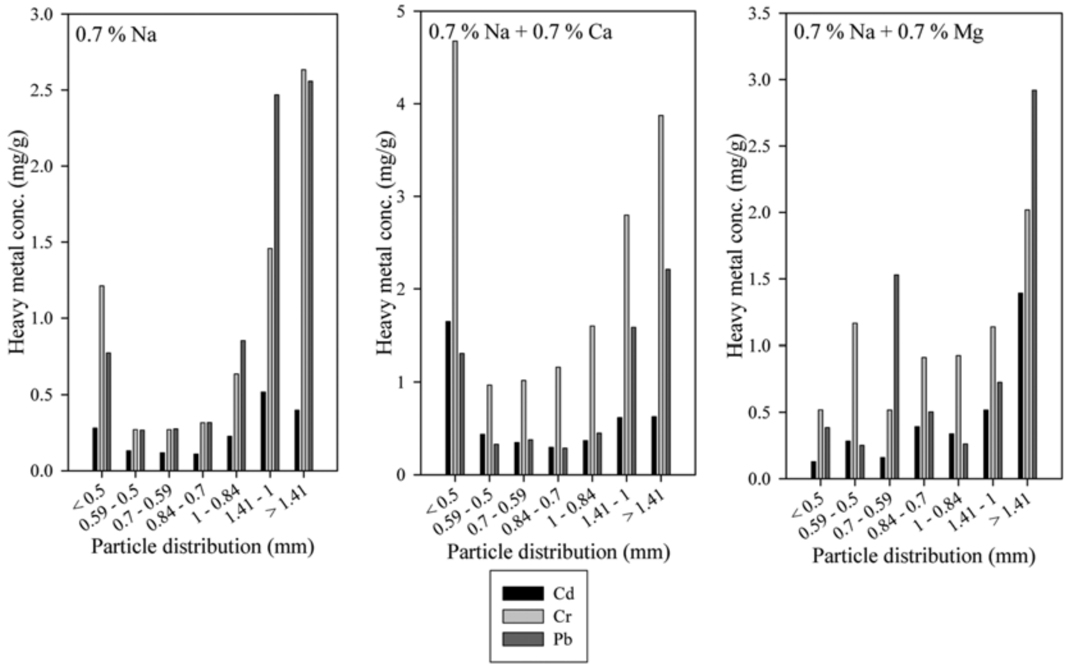

Fig. 5. Heavy metal distributions in sand bed with different additives (800 °C).

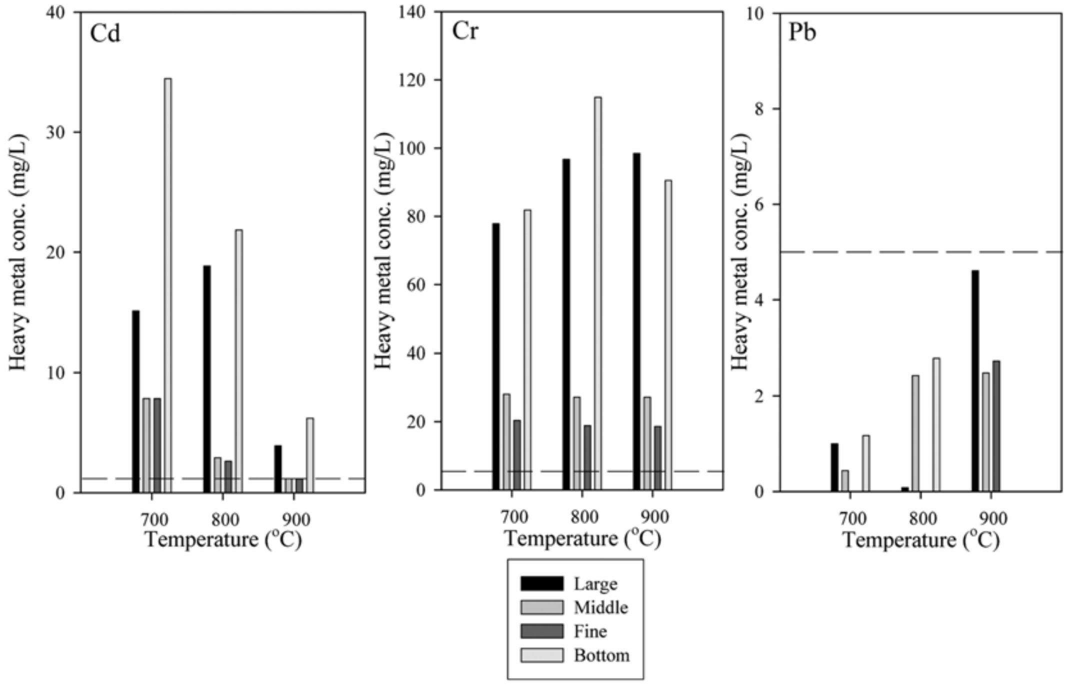

Fig. 6. The TCLP result of sand bed for different operation temperatures (0.7% Na). (Dashed line is the threshold of law, Cd: 1 mg/L, Cr: 5 mg/L and Pb: 5 mg/L).

the time for defluidization, so the operating time is short, the feed rate is reduced, and the heavy metals accumulated in the bed materials are limited. Therefore, the leaching quantity decreases as the Na concentration increases.

2-3. Bed Material Heavy Metal Leaching with Addition of Different Materials

Fig. 8 shows the Cd, Cr, and Pb leaching concentrations of TCLP with different additions. Comparison of the leaching with and without the addition of Ca and Mg indicates that when Ca and Mg are added, as the alkaline earth elements can prolong agglomeration/defluidization, the addition of Ca and Mg would extend the operating time, so more heavy metals in the bed materials are accumulated in the sand bed. When the three heavy metals are added with the alkaline earth elements, the heavy metal leaching concentra-

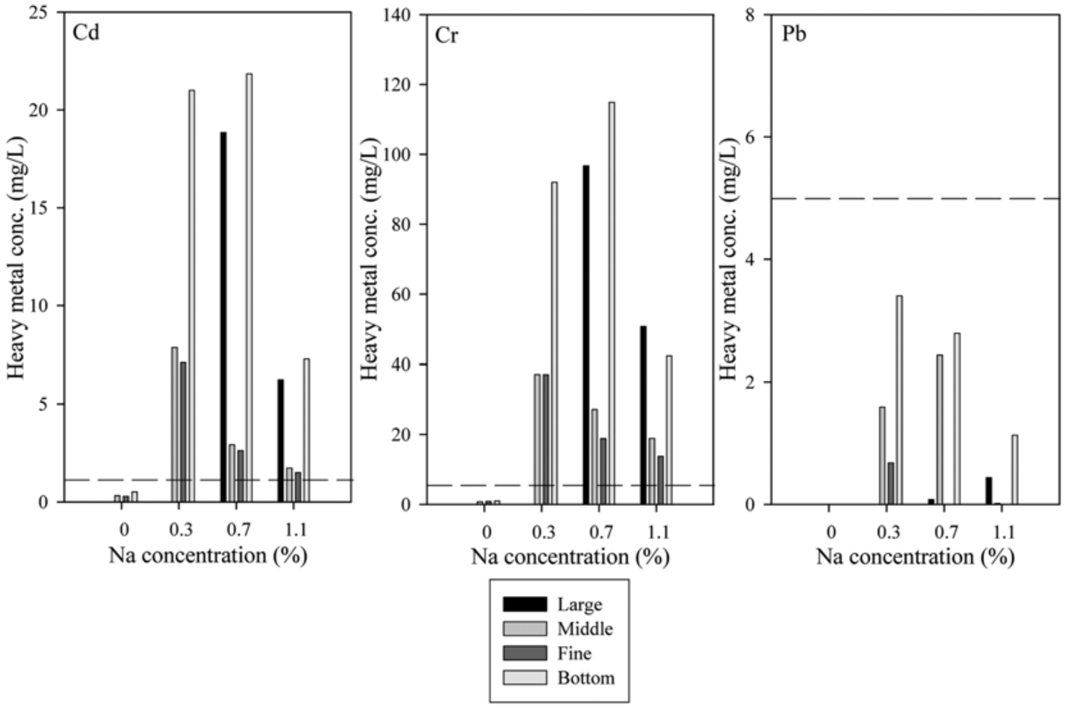

Fig. 7. The TCLP result of sand bed for different Na concentrations (800 °C). (Dashed line is the threshold of law, Cd: 1 mg/L, Cr: 5 mg/L and Pb: 5 mg/L).

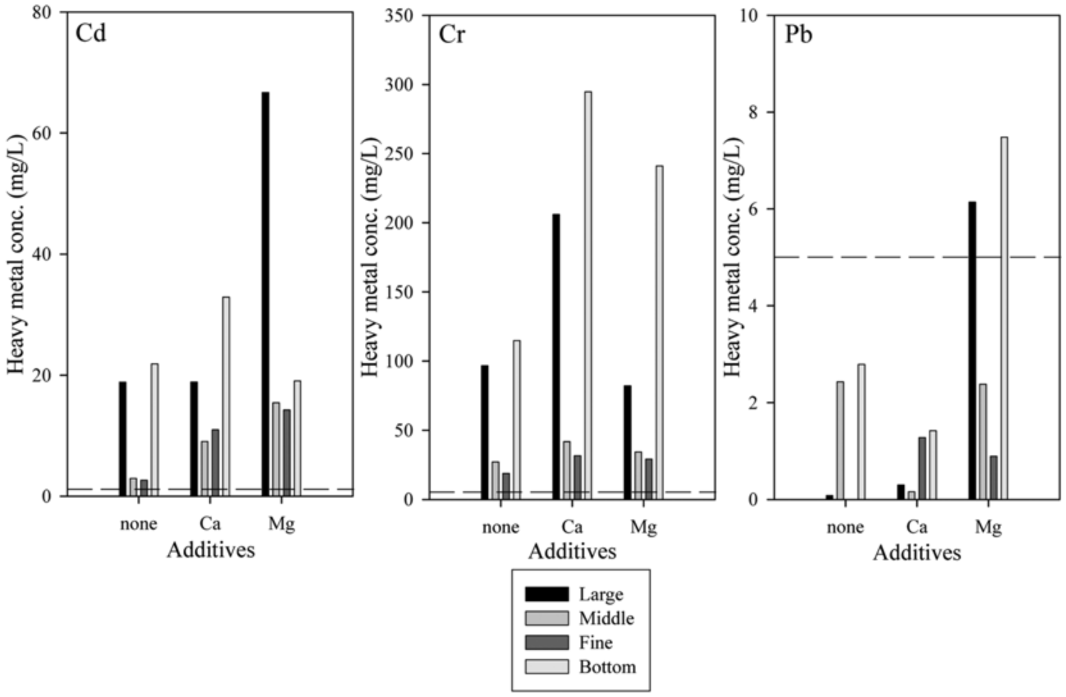

Fig. 8. The TCLP result of sand bed for different additives (800 °C and 0.7%Na). (Dashed line is the threshold of law, Cd: 1 mg/L, Cr: 5 mg/L and Pb: 5 mg/L).

tions in the bed materials would increase.

3. Results of *Vibrio fischeri* Test - EC_{50}

After TCLP of bed materials in different test processes, the leaching solutions are collected for the heavy metal concentration analysis, and then the *Vibrio fischeri* test is conducted for the leaching solutions. Fig. 9 shows the results of the *Vibrio fischeri* test. As seen, the bed material heavy metal leaching solutions have the maximum biological toxicity in the operation at 700 °C and 0.3%Na. This may be because the low operating temperature and Na concentration prolong the agglomeration/defluidization, so that the fluidized bed oper-

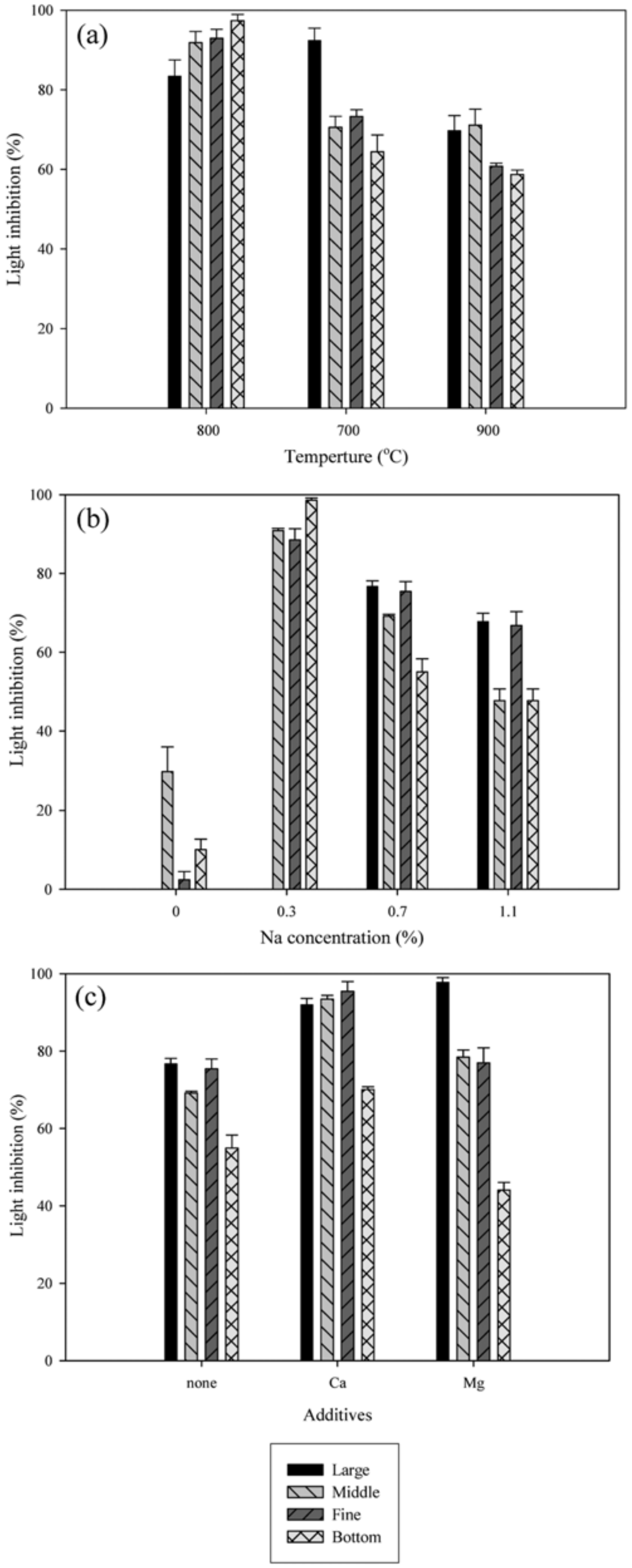

Fig. 9. The toxicity evolution result of different operations (a) different operating temperature, (b) different Na concentration, (c) different additives.

ating time is longer, and a large amount of feed heavy metals are accumulated on the bed material. As a result, the heavy metal leaching concentration increases, and the leaching solution has a high toxicity to organisms. Furthermore, the addition of Ca and Mg to the waste can prolong the agglomeration/defluidization, so a large amount of feed heavy metals are accumulated on the bed material, and the biological toxicity with the addition of Ca and Mg is higher than that without the addition. Based on the results of different particle sizes, the biological toxicity caused by heavy metals that are caught in the large, medium, small and fine grains does not have a definite trend, though the heavy metal concentrations in large and fine particles are higher than that in the medium and small particles. The heavy metals contained in the medium and small particles may not be tolerated by organisms, so there is no significant difference in the biological toxicity.

CONCLUSIONS

This study explored the influence of different fluidized operating parameters on the bed material heavy metal distribution and biological toxicity. The changed operating parameters are the Na content, operating temperature and addition of alkaline earth elements. The experimental results showed that the bed material size distribution inclines towards small grain sizes as the operating temperature increases. When there is Na, as the eutectic material produces agglomerates, the particle size increases. As for the bed material heavy metal distribution, fine particles have a smaller surface area, and the heavy metals are more likely to adsorb to the surface. The heavy metals in large size are adhered to the eutectic materials on the surface of the agglomerates, so the heavy metal concentrations in large and fine particles increase. In consideration of the bed material heavy metal distribution, Cr and Pb exhibit the maximum contents, which may be because the boiling points of the compounds of Pb and Cr are high, so they are more likely to exist in the bed material. As the operating temperature increases, the overall concentration of heavy metals decreases. This is because the defluidization is likely to happen at a higher temperature when the operating time is relatively short. In addition, when the Na concentration in the fed material increases, the heavy metal content in the bed material decreases, because when the Na concentration is low, it requires a longer time to accumulate Na, in order to form agglomeration/defluidization. Thus, a large amount of heavy metals are accumulated.

As for the evaluation of the impact of bed materials on the environment, according to TCLP, the bed materials with large and fine particle sizes have the maximum heavy metal leaching concentrations, and heavy metals Cd and Cr are most obvious, where the leaching values of Cd and Cr exceed the regulatory standards. As the Na concentration in the fed material increases, the operating time is shortened, so the leaching quantity decreases as the Na concentration increases. The addition of Ca and Mg can prolong the agglomeration/defluidization and increase the heavy metal leaching. As for the biological toxicity test, the biological toxicity is at its maximum at 700 °C and 0.3%Na, which may be because the operating time is longer, and the heavy metal concentration in the bed material is higher. Different particle sizes do not have large differences in toxicity, which is because the heavy metal content in different particle sizes cannot be tolerated by organisms. Therefore, the heavy metal leaching and biological toxicity should be concerned in the subsequent treatments of the incinerated bottom ash.

ACKNOWLEDGEMENTS

The authors thank the National Science Council of the Republic of China, Taiwan for financially supporting this research under Contract NSC 96-2221-E-390-031-MY3.

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