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Study of the low-temperature two-stage fluidized bed incineration: Influence of the second-stage sand bed operating conditions on pollutant emission

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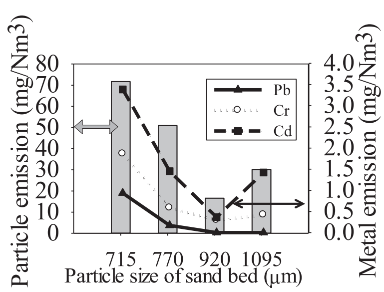
HIGHLIGHTS

- Particle emission was correlated with the organic and heavy-metal emissions.
- Organic pollutants could be controlled efficiently after second-stage treatment.
- Bubble-phase ratio and void size in second sand bed were the major factors.
- Flat-type of second sand bed has a better metal and particle control efficiency.

GRAPHICAL ABSTRACT



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ABSTRACT

To better understand the mechanism of the second-stage sand bed in controlling the pollutant emissions from a low-temperature two-stage fluidized bed (LTTSFB) incinerator, different parameters of the second-stage sand bed, including the particle size, bed height, and particle size distribution (PSD), were determined in this study. Artificial waste that contained heavy-metals (Pb, Cr, and Cd) was used to simulate municipal solid waste (MSW). Particle, heavy-metal, and organic—polyaromatic hydrocarbon (PAH) and benzene, toluene, ethylbenzene, and xylene (BTEX)—pollutant emissions were the main concerns. During the initial test, the removal efficiency of the BTEX and PAH pollutants were between 70% and 76% after the second-stage treatment. The results also showed that the particle emission was correlated with the organic and heavy-metal emissions. Compared with the different particle sizes in the second-stage, the bubble-phase ratio and the sizes of voids in the sand bed were observed to be the major factors that controlled the pollutant emissions. Greater secondary sand-bed height also resulted in a greater likelihood of trapping the particles and heavy metals. But, it had a limitation. With respect to the PSD in second-stage, the results revealed that a flat-type distribution exhibited better efficiency in controlling the particle and metal emissions.

1. Introduction

Incineration is a feasible technology for the disposal of municipal solid waste (MSW). In addition to generating electricity, it also plays an important role in avoiding the spread of pathogens. In many island countries, waste management becomes a difficult task

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owing to their limited space for landfills and high population density. Therefore, incineration, which results in high mass and volume reductions, is the primary option. However, with the construction of numerous incinerators, the residues produced by incineration have become a major concern. Because the composition of MSW is complex, numerous types of hazardous mutagenic byproducts may be generated during the incineration process, including heavy metals, dioxin, and acidic gases [1–4]. Among the different types of organic pollutants, polycyclic aromatic hydrocarbons (PAHs) are often a main target for removal because of their close relationship with dioxin [5]. In general, PAHs can be effectively controlled at higher combustion temperatures [6]. However, some incombustible heavy metals would vaporize easily at such temperatures because of their low boiling points. These volatile metals would be emitted easily as fine particles formed by nucleation, coagulation, and agglomeration [7]. Currently, the fly ash from incinerators is always considered as hazardous waste because of its high concentration of heavy metals [8,9]. Thus, other alternatives need to be developed.

Among the different kinds of incinerator designs, the fluidized bed reactor allows operation at lower temperatures and exhibits high conversion efficiency because of its thorough mixing and high heat and mass transfer [10–12]. Previous studies have noted that a fluidized bed incinerator can reduce the leaching rate of the heavy metals in the resulting residue [13]. Recently, another innovative technology known as low-temperature two-stage fluidized bed (LTTSFB) incineration was developed for the treatment of MSW [14]. Compared with a traditional high-temperature fluidized bed incinerator, the LTTSFB design not only generates lower heavy-metal emissions but also costs less. In an LTTSFB incinerator, two mechanisms control the emission of metals. The first mechanism is the low-temperature control at the first reactor. Because of the lower combustion temperature, the metals are not easily vaporized; therefore they have a higher chance of remaining in the first stage. However, this control method depends on the characteristics of the metals. The other mechanism relies on filtration at the second stage. Actually, previous studies have reported that a fluidized bed reactor can be operated as a filtration system [15–19]. The results of these previous studies show that the filtration efficiency of the fluidized bed is related to the operating flow rate, bed temperature, and particle size distribution (PSD) of the bed materials. Geldart [20] has studied the effects of the particle size and the PSD of the sand in a fluidized bed on the behavior of fluidization. Their results indicated that the mean particle size of the bed media is more important than its PSD. As the mean particle size was decreased, the minimum fluidization velocity (U_{mf}) was altered. Furthermore, the bubble size and bubble rise velocity were also affected. However, other previous studies have demonstrated that the PSD of the bed material affects the fluidization behavior, including the aeration of the dense phase, the void size, bed expansion, the number of particles in voids, and the reaction efficiency [21–24]. Any such changes in the fluidization behavior will alter the combustion efficiency [25,26].

To summarize the previous literature, the behaviors of fluidization can affect the filtration and reaction efficiency. In previous studies, researchers focused only on the removal efficiency of organic pollutants or on the filtration of inorganic matter in a fluidized bed under different PSDs or particle diameters. With respect to the LTTSFB system, the design of the second-stage fluidized bed becomes a critical issue because the flue gas may contain not only unburned carbon but also incombustible residue. In addition, any change in fluidization resulting from a change in the configuration of the second stage will undoubtedly affect the organic pollutant control and metal emissions. Thus, this issue needs to be investigated further. Accordingly, the aim of this study is to determine the effect of the second-stage fluidized bed operating conditions on pollutant control during LTTSFB incineration. The particle, PAH and benzene, toluene, ethylbenzene, and xylene (BTEX), and heavy-metal emissions were the main evaluated parameters. First, to provide the basic information related to pollutant emissions, the LTTSFB incinerator was tested at different first-stage temperatures. The second-stage parameters, including the particle size, bed height, and PSD, were subsequently tested during the incineration process. These results are helpful in understanding the relationship between the different second-stage operating conditions and the pollutant emissions; they also provide useful information for the design of the second stage in LTTSFB systems.

2. Materials and methods

2.1. Experiment materials

In this study, artificial waste was used to simulate MSW. The main composition of the artificial waste was wood chips, which were contained in polyethylene (PE) bag. A heavy-metal solution was prepared and subsequently added to the PE bag containing the wood chips. Three metal salts were chosen: $Pb(NO_3)_2$, $Cr(NO_3)_3 \cdot 9H_2O$, and $Cd(NO_3)_2 \cdot 4H_2O$. The concentration of each metal in the waste was 0.1 wt.% as the atoms of metals without nitrates. The waste feed rate was 9.4 g/min. The detailed proximate and elemental analyses of each material are referred from our previous study [14]. The fluidized media was silica sand, which was acquired from the Chih-Chuen Industry Co. in Taiwan. The density of the sand was 2600 kg/m^3. The composition of the silica sand was 97.8% SiO_2, 2.01% Al_2O_3, and 0.07% Fe_2O_3. Both the physical and chemical characteristic data were supplied by the manufacturer. A uniform size of the silica particles was obtained using a Tyler sieve. Table 1 shows the four types of PSDs (Narrow, Binary, Flat, and Gaussian) used in this study. The classification of these distributions is referred from previous work [21]. The detailed operating conditions are shown in Table 2.

2.2. Apparatus and procedure

A schematic of the LTTSFB incinerator is shown in Fig. 1. This system comprised a first-stage and a second-stage reactor. Both stages were constructed of stainless steel (AISI 316SS), and their

Table 1
The particle size distributions of different powder types.

Different types	Weight (%) x_i[a]	Sieves (μm)	Average diameter d_{pi}[b] (μm)	d_{sv}[c] (μm)
Narrow	100	590–840	715.0	715
Flat	17	350–500	425.0	719
	17	500–701	600.5	
	19	701–840	770.5	
	23	840–1000	920.0	
	24	1000–1190	1095.0	
Binary	59	840–1000	920.0	719
	41	500–590	545.0	
Gaussian	8	350–500	425.0	719
	25	500–701	600.5	
	35	701–840	770.5	
	23	840–1000	920.0	
	9	1000–1190	1095.0	

[a] x_i: weight fraction (%).
[b] d_{pi}: Average diameter between the sieves (μm).
[c] d_{sv}: surface/volume diameter(μm); the d_{sv} calculation formula is: $d_{sv} = 1/\sum_i x_i/d_{pi}$.