ELSEVIER

Chemosphere 56 (2004) 911–922

CHEMOSPHERE

www.elsevier.com/locate/chemosphere

Relationship between pressure fluctuations and generation of organic pollutants with different particle size distributions in a fluidized bed incinerator

Chiou-Liang Lin, Ming-Yen Wey *, Han-Tsung Cheng

Department of Environmental Engineering, National Chung-Hsing University, 250 Kuo-Kuang Road, Taichung 402, Taiwan, ROC

Received 1 October 2003; received in revised form 24 March 2004; accepted 22 April 2004

Abstract

The hydrodynamic behaviors of fluidization perhaps significantly influence the uniformity of fluidization in fluidized bed incinerator. Good uniformity of fluidization expressed the air across uniformly through the bed and the particles being distributed well in the fluid stream. The aggregates, flocs and channels of particles do not happen during fluidization. The Good uniformity will maintain high heat and mass distribution to improve reaction efficiency. These parameters include the height of static bed, gas velocity, mixing and distribution of bed particle, which have rarely been studied in previous investigations. Consequently, this study examines how the hydrodynamic parameters affect the generation of organic pollutants (BTEXs and PAHs) during incineration. The statistical and power spectral analysis of the measured pressure fluctuation during incineration are used to elucidate the relationship between behaviors of fluidization and generation of pollutants during incineration.

Experimental results show the organic concentration does not increase with uniformity of fluidization decreasing. The reason may be the explosion of the gas and the consequent thermal shock destroy the coalescent bubbles to form small bubbles again and enhance the efficiency of transfer of oxygen to increase combustion efficiency. Additionally, the mean amplitude and fluidized index of pressure fluctuation similarly vary with the concentration of organic pollutants. These two indices can be used to assess the efficiency of combustion. The four particle size distributions could be divided into two groups by statistical analysis. The Gaussian and narrow distributions belong to one group and the binary and flat the other. The organic concentration of the Gaussian and narrow distributions are lower than that of the other distributions. Consequently, the bed materials should maintain narrow or Gaussian distributions to maintain a good combustion efficiency during incineration.

Keywords: Incineration; PAHs; BTEXs; Pollutant; Pressure fluctuation

1. Introduction

The development of incineration technology has been the focus of global research for several years; such technology is considered to be effective for disposing of waste. This approach has many advantages, such as, the reduction of waste and the recovery of energy, and the method has become a promising method for treating waste. The fluidized bed incinerator has been extensively employed to dispose waste due to its advantages that include good solid mixing, high heat transfer and large contact surface area, among others (Nam et al., 2002).

* Corresponding author. Tel.: +886-4-22852455; fax: +886-4-22862587.

E-mail address: mywey@dragon.nchu.edu.tw (M.-Y. Wey).

0045-6535/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.chemosphere.2004.04.046

Nomenclature

F	flatness defined in Eq. (4)
f_p	dominant frequency of pressure fluctuations (s^{-1})
$f(x)$	probability density function of x
T	duration of sampling (s)
S	skewness defined in Eq. (3)
S_{xx}	power spectral density function
x	random signal values of pressure fluctuations (Pa)
$\bar{x}$	mean value of random signals in pressure fluctuations (Pa)
$x(t)$	random variables
τ	time shift variable in Eqs. (1) and (2) (s)
ϕ_{xx}	auto-correlation function of $x(t)$
ω	angular frequency
δ_p	average deviation of amplitude of pressure fluctuations [–]

Some important parameters influence the operation of the fluidized bed, such as the height of the static bed, operating velocity of the gas and the particle size distribution (PSD). Attrition and combustion increase the number of particles and alter PSD, which may influence the performance of the reactor, in terms of fluidizing characteristics and stability of operation (Bemrose and Bridgwater, 1987). PSD is governed by several parameters including the minimum fluidization velocity, the terminal velocity, the elutriation rate and reaction efficiency. Changes in PSD could affect hydrodynamic behavior (Ray and Jiang, 1987; Pell et al., 1990). Arena et al. (1983) and Chirone et al. (1985) demonstrated that particle sizes were changed not only by fluid-dynamics but also by thermal shock and combustion. The narrow PSD reduces defluidization and segregation, but a wide PSD enhances conversion and fluidity (Gauthier et al., 1999). Consequently, PSD is an important parameter of the operation of the fluidized bed reactor.

Many investigators have analyzed pressure fluctuations in the chamber of the gas-fluidized bed to assess the uniformity of fluidization. The pressure fluctuations were related to the effects of the formation, coalescence and escape of bubbles on bed height (He et al., 1997; Van Der Schaaf et al., 1998). Several important parameters, such as operating temperature, static bed height, operating gas velocity and the characteristics of the bed material, affect the pressure fluctuations and thereby change the uniformity of fluidization (Lee and Kim, 1988; Sun and Grace, 1992). Morse and Ballou (1951) firstly used pressure fluctuation to evaluate the uniformity of fluidization. They used a small amplitude and a high frequency of fluctuation improve fluidization, and Kai and Furusaki (1985) obtained the same result.

However, several parameters, like operating temperature, amount of excess air, mixing of bed materials and operating gas velocity, affect not only the hydrodynamic behaviors of fluidization but also the generation of pollutants during incineration. In a fluidized bed incinerator, the amount of oxygen increases with the amount of excess air, reducing residence time and increasing bubble size to reduce the mixing of bed materials. The size of particles of the bed materials also affects the efficiency of reaction and the hydrodynamic behaviors of fluidization. Chiang et al. (1992) pointed out that the organics with low molecular weight was generated easily when the sand bed was stirred unevenly, generating locally low temperatures (400–500 °C). High temperatures (700–900 °C) will promote the generation of high-ring species, such as those with five or six rings. In a lack of oxygen, the degradation of polymer tends toward a pyrolysis reaction and the emission of volatile organics (Zhang, 1998). Therefore, the uniformity of fluidization directly affects the generation of pollutants. Besides organic pollutants, the carbon ash is also emitted from flue gas during incomplete combustion. These particles provide surfaces for capturing volatilized metals by heterogeneous deposition and adsorbing organics to provide active sites to transfer low-ring species to high-ring (Wey et al., 1996; Durlak et al., 1998; Wey et al., 1998). The generation of fly ash not only reduces the efficiency of combustion but also impacts the generation of organics. Consequently, the effect of these parameters on the uniformity of fluidization and pollutant generation must be considered simultaneously.

According to previous research, the behaviors of fluidization affect the mixing and reaction efficiency. The generation of air pollutants is influenced by operating conditions. However, the relationships between the hydrodynamic behaviors of fluidization and the generation of air pollutants have rarely been studied in previous investigations. Therefore, this investigation focuses on further evaluating the effects of hydrodynamic behaviors of fluidization at high temperatures on the generation of pollutants during incineration. Pressure fluctuations will be measured and statistics and powder spectra used to analyze the uniformity of fluidization. The pollutants are sampled during incineration. Then, the effect of the uniformity of fluidization on the generation of pollutants during incineration is analyzed. Experimental studies are performed at over 800 °C on silica sand with four different PSDs (narrow powder, binary mixture, flat and Gaussian powder). The effects of the height of static bed and the velocity of the operating gas are studied.

2. Experimental

2.1. Experimental procedures

Fig. 1 depicts the apparatus used in the experiment, including a bubbling fluidized bed incinerator. The incinerator included a preheated chamber (length 500 mm), a main chamber (height 1100 mm) with an inner diameter of 100 mm, and an expanding section (height 1000 mm) with an inner diameter of 250 mm. The reactor was made of 3 mm thick stainless steel (AISI 310), and was equipped with a stainless steel porous plate with a 15% open area through which to distribute gas. The temperature was controlled by a PID controller and three thermocouples were used to measure the temperature; the temperature was fed back to the controller. The apparatus also included a data acquisition system (ADVANTECH PC-LabCard PCL-711S and VisiDAQ Professional Version 3.1) to record the temperature and fluctuating pressure signals in the fluidized bed. Two cyclones were connected to a bag filter to collect the fly ash from the combustion chamber.

Silica sand was used as the bed material in the experiment, and had an almost constant density for all sizes ($\rho_p = 2600\ \mathrm{kg\,m^{-3}}$). Four types of PSD were studied: a narrow powder, a binary mixture, a flat and similar Gaussian distribution powder all with nearly the same mean diameter ($d_p = 719\ \mu\mathrm{m}$). These types of PSD were prepared according to the method suggested by Gauthier et al. (1999). Table 1 presents the components of the four types of PSDs. The experimental procedure started by preheating the sand bed to the desired temperature (800 °C), after which air was passed through the preheated chamber to increase the temperature. The minimum fluidization velocity was determined from the Δ_p-versus-U_0 diagram. The detail method of measured minimum fluidization velocity refers to Lin et al. (2002). According to the required gas flow of fluidization, the different masses of the artificial wastes were prepared and the excess gas was 40%. Table 2 lists the weights of artificial wastes (polypropylene, PP) under various conditions and operating conditions. PP was fed into the chamber and the pressure fluctuations were simultaneously recorded. When the experiment was complete and the temperature reduced, all bed materials in the combustion chamber and the fly ash in the cyclone and the bag filter were collected and then the process was repeated under other conditions.

2.2. Measuring and analyzing pressure fluctuations

Two pressure detectors were used to measure the difference between the pressure of the sand bed and that of the freeboard. One end of the tube was covered with a 200 mesh screen to prevent the particles from entering the tube, and the other end was connected to different pressure transmitter (Huba Control 692). These pressure

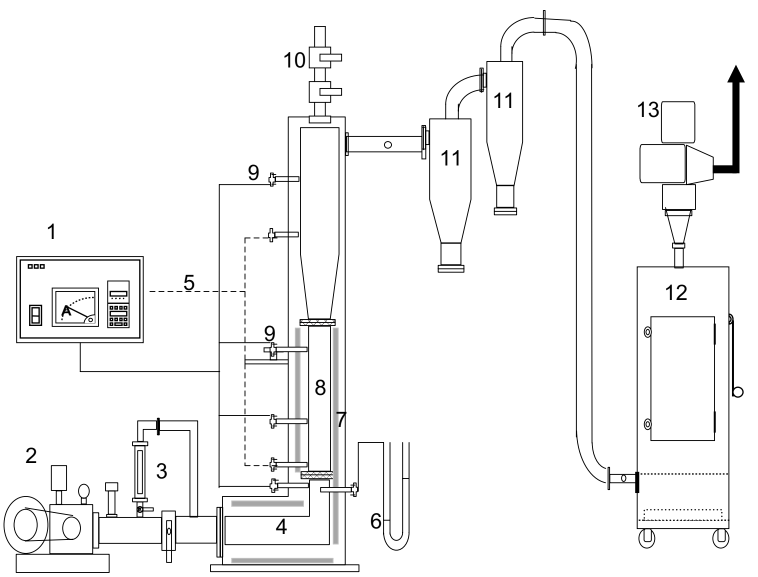

Fig. 1. The bubble fluidized bed incinerator. (1) PID controller, (2) blower, (3) flow meter, (4) preheater chamber, (5) pressure transducer, (6) U manometer, (7) electric resistance, (8) sand bed, (9) thermocouple, (10) feeder, (11) cyclone, (12) bag filter, (13) induced fan.

Table 1
The components of four types of PSD

Type of PSD	Sieves (μm)	Average diameter (μm)	The percentage of total weight (%)	Total weight of different static bed height (g)		
				100 mm	200 mm	300 mm
Narrow	590–840	715.0	100	1120	2240	3360
Gaussian	350–500	425.0	8	1120	2240	3360
	500–701	600.5	25			
	701–840	770.5	35			
	840–1000	920.0	23			
	1000–1190	1095.0	9			
Binary	840–1000	920.0	59	1120	2240	3360
	500–590	545.0	41			
Flat	350–500	425.0	17	1120	2240	3360
	500–701	600.5	17			
	701–840	770.5	19			
	840–1000	920.0	23			
	1000–1190	1095.0	24			
			d_{sv} = 719 μm			

Table 2
The operating conditions for each experiment

Run	Type of PSD	Static bed height (mm) (H/D)	Influent air ($l\,min^{-1}$) (U_{mf})	Feed rate of PP ($g\,15\,s^{-1}$)
1	Binary	200 (2)	120 (1.3)	1.55
2	Flat	200 (2)	113 (1.3)	1.45
3	Gaussian	200 (2)	109 (1.3)	1.40
4	Narrow	200 (2)	117 (1.3)	1.53
5	Binary	200 (2)	138 (1.5)	1.83
6	Flat	200 (2)	131 (1.5)	1.70
7	Gaussian	200 (2)	126 (1.5)	1.65
8	Narrow	200 (2)	135 (1.5)	1.78
9	Binary	200 (2)	156 (1.7)	2.08
10	Flat	200 (2)	148 (1.7)	1.95
11	Gaussian	200 (2)	143 (1.7)	1.88
12	Narrow	200 (2)	153 (1.7)	2.03
13	Binary	100 (1)	138 (1.5)	1.83
14	Flat	100 (1)	131 (1.5)	1.70
15	Gaussian	100 (1)	126 (1.5)	1.65
16	Narrow	100 (1)	135 (1.5)	1.78
17	Binary	300 (3)	138 (1.5)	1.83
18	Flat	300 (3)	131 (1.5)	1.70
19	Gaussian	300 (3)	126 (1.5)	1.65
20	Narrow	300 (3)	135 (1.5)	1.78

PP = polypropylene.

probes, which were 9 mm in diameter and 250 mm in length, were made of stainless steel and inserted into the middle of the sand bed. The range of measurement by the different pressure transmitter was 0–1000 mmH_2O. The pressure signals were digitized and recorded by a data acquisition system. The sampling interval was 10 ms and 8192 points were recorded for each experiment. These data were analyzed for mean amplitude, skewness, flatness and dominant frequency, by statistical and power spectral analysis.

2.3. Sampling and analyzing organics

During incineration, small amount pollutant may emit during incomplete combustion. Some of these compounds, volatile organic compounds (VOC) have generated considerable interest because of their harmful effects. The VOC plays an important role in the formation of ozone and photochemical oxidants (Lee et al., 2002). However, these compounds bas been reported by some stack gas and ash residues (Wheatley and Sadhra, 2004). The effect of operation parameters was rarely studied on generation of VOCs. The Polycyclic aromatic hydrocarbons (PAHs) are semivolatile organic compounds those includes two benzene-ring to six benzene-ring compounds. Single ring compounds are abbreviated as BTEXs, those contain benzene, toluene, ethyl-benzene and *m*-, *p*-, *o*-xylene. Table 3 lists the classifications and abbreviations of organic compounds (BTEXs and PAHs). Amount of the VOC species, BTEXs were the major compounds (Arion et al., 2001; Lee et al., 2002). Additionally, several of PAH compounds are known carcinogens and mutagens that impair human health. Due to these compounds are harmful human, 16 PAHs are restricted by the US Environmental Protection Agency (EPA).

Table 3
Classifications and abbreviations of organic compounds (BTEXs and PAHs) in this study

BTEXs	Abbreviation
Single benzene-ring compounds	
Benzene	
Toluene	
Ethyl-benzene	
m-Xylene	
p-Xylene	
o-Xylene	
PAHs	
Two benzene-ring compound	
Naphthalene	Nap
Three benzene-ring compounds	
Acenaphthylene	AcPy
Acenaphthene	AcP
Fluorine	Flu
Phenanthrene	Pha
Anthracene	Ant
Four benzene-ring compounds	
Fluoranthene	FluA
Pyrene	Pyr
Benzo(*a*)anthrancene	B(*a*)A
Chrysene	Chr
Five benzene-ring compounds	
Benzo(*b*)fluoranthene	B(*b*)F
Benzo(*k*)fluoranthene	B(*k*)F
Six benzene-ring compounds	
Benzo(*a*)pyrene	B(*a*)P
Dibenzo(*a*,*h*)anthracene	DbA
Benzo(*g*,*h*,*i*)perylene	B(*g*,*h*,*i*)P
Indeno(1,2,3-*cd*)pyrene	InP

According to Gulyurtlu et al. (2003), there has a strong correlation between the combustion efficiency and the PAHs emission. The generation of carbon monoxide and PAHs had the same tendency. In order to understand the effect of operation parameters on generation of pollutants, the BTEXs and PAHs were select to represent the volatile and semivolatile organic compounds and analyze the relationship between behaviors of fluidization and generation of pollutants during incineration.

Flue gas, containing organics, was sampled by isokinetic sampling. US EPA Modified Method 5 was used for sampling and the sampling apparatus were as depicted in Fig. 2. The sampling apparatus included a stainless sampling probe, a glassy filter holder, impingers, a flow meter and a vacuum pump. The flue gas flowed through a glassy fiber to sample the fly ash. Then, it was passed through a cooling tube to cool the flue gas and the organic compounds were adsorbed by XAD-4 resin. The glassy fiber, which contained fly ash, and XAD-4 resin were extracted for 20 h by the Soxhlet extraction process and condensed to 1 ml using a Kuderno Danish evaporative concentrator. These two samples reflected on organic pollutants in solid and gas phases, respectively. Finally, these samples were stored at 4 °C. Then, these samples were analyzed using a gas chromatograph/flame ionization detector. The recovery efficiency was analyzed to identify the precision and the accuracy of the analytical procedure. The recovery efficiency of BTEXs and PAHs was approximately 90%.

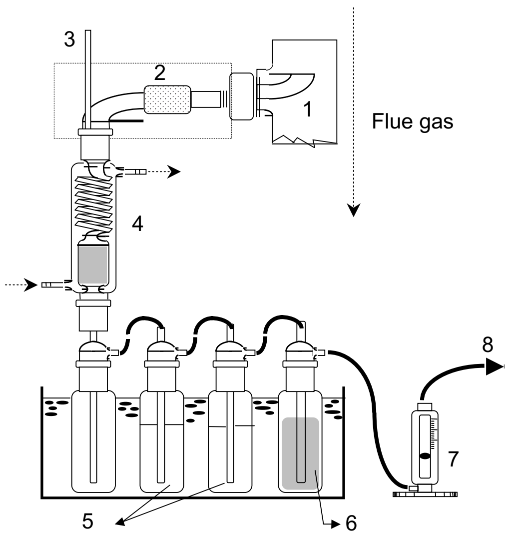

Fig. 2. Sampling train for organics. (1) Sampling probe, (2) fiber glass, (3) thermometer, (4) cooling tube and XAD-4 adsorption tube, (5) 100 ml distilled water, (6) silica gel, (7) flow meter, (8) vacuum pump.

3. Results and discussion

3.1. Distribution of BTEXs and PAHs on gas and solid phases at various conditions

Fig. 3 present the typical results of organic pollutants in gas and solid phases. Under all conditions, the distribution of organic pollutants in the gas and solid phases were similar. Fig. 3 shows that the BTEXs and the two-ring PAHs (Nap, Acpy, Acp and Flu) are most distributed in the gas phase. The most of high-ring PAHs (three to six rings) are distributed in solid phase. Chiang et al. (1992) pointed out that a high temperature of 700–900 °C promoted the generation of five and six-ring PAHs. Griest and Tomkins (1986) and Durlak et al. (1998) also implied that the ability of adsorption of organics on fly ash increased with an increase in the number of benzene rings in the organic components. At the same temperature and concentration, the high-ring organic pollutants have a high capacity to be adsorbed on the fly ash. Wey et al. (1996, 1998) also pointed out that the simultaneous presence of fly ash and heavy metal provides active sites for the reaction of the PAHs. Therefore, when the low-ring PAHs condense on the surface of the fly ash, the active sites, which contain carbon or heavy metals, will catalyze the formation from low-ring species to five and six ring PAHs. Therefore, most of these high-ring PAHs are distributed in the solid phase.

Fig. 4 illustrates the PAHs and BTEXs concentrations in the flue gas. The amount of organic pollutants increases with the gas velocity, because the gas residence time in the sand bed decreases. However, a gas velocity maintained at 1.5 and 1.7 U_{mf} yielded similar amounts of generated organic pollutants. The concentration of organic pollutants decreases as the bed height increases.

3.2. Dominant frequency and mean amplitude of pressure fluctuations

The power frequency spectrum is measured by taking the Fourier transform of the auto-correlation function of a pressure fluctuation signal. The calculation functions are defined as

$$\varphi_{xx}(\tau) = \lim_{T\to\infty} \frac{1}{T} \int_{\frac{-T}{2}}^{\frac{T}{2}} x(t)x(t+\tau)\,dt \tag{1}$$

$$S_{xx}(\omega) = \int_{-\infty}^{\infty} \varphi_{xx}(\tau)e^{-\omega t}\,d\tau = 2\int_{-\tau_m}^{\tau_m} \varphi_{xx}(\tau)\cos 2\pi f\tau\,d\tau \tag{2}$$

Fig. 5 presents the dominant frequency of the pressure fluctuations. Fig. 5 shows that the dominant frequency increases with gas velocity, at a low gas velocity. However, when the gas velocity exceeds 1.5 U_{mf}, the dominant frequency begins to decline. Kai and Furusaki (1985) revealed that reducing the amplitude of pressure fluctuations and the bubble size, and increasing the main frequency, improved the uniformity of fluidization. According to earlier studies, the uniformity of fluidization is best when the operating gas velocity is maintained at 1.5 U_{mf}. From Fig. 5, the dominant frequency of the

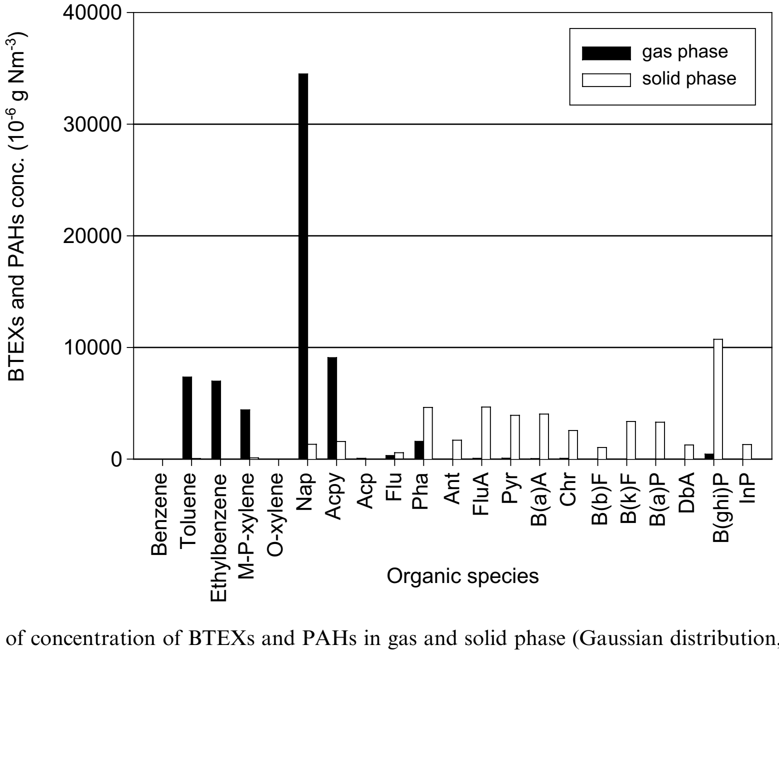

Fig. 3. The distribution of concentration of BTEXs and PAHs in gas and solid phase (Gaussian distribution, 2.5 H/D and 1.5 U_{mf}).

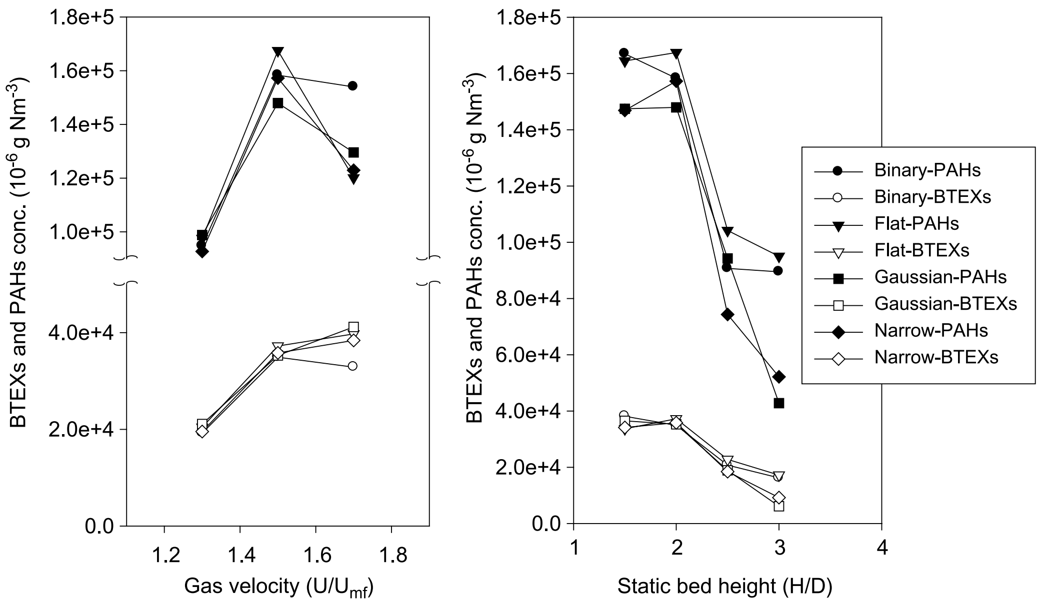

Fig. 4. BTEXs and PAHs concentration in flue gas at different gas velocity and static bed height.

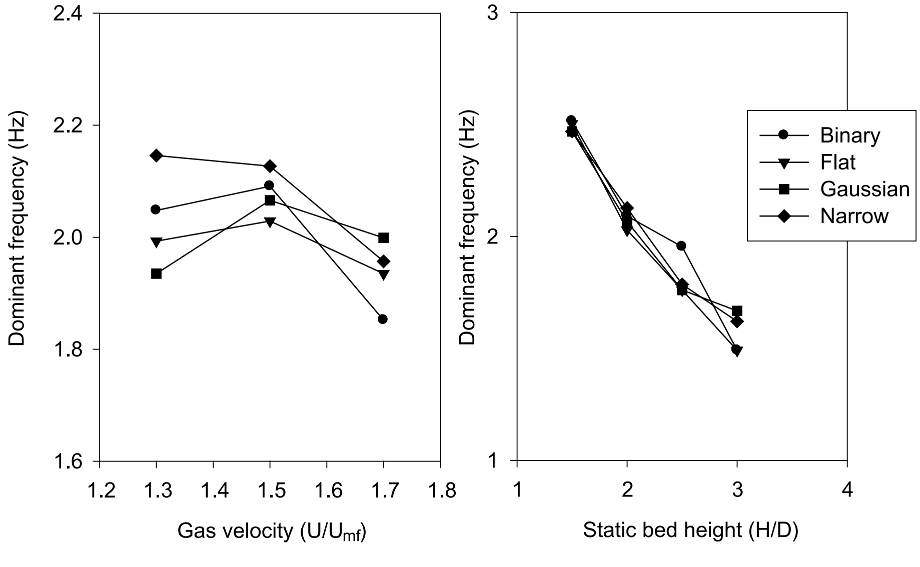

Fig. 5. Dominant frequency of pressure at different gas velocity and static bed height.

four PSDs decreases as the static bed height increases, implying a decrease in the uniformity of fluidization because the sources of pressure fluctuations increase to reduce dominant frequency.

Fig. 6 show the mean amplitude of pressure under various conditions. According to two-phase theory, the increase in the mean amplitude is attributable to the increase in bubble size, when the operating gas velocity exceeds the minimum fluidization velocity. Meanwhile, slugs may increase the amplitude of pressure fluctuation as the velocity of the gas increases (Sadasivan et al., 1980; Svoboda et al., 1983; Fan et al., 1990; Leu and Lan, 1990). The increasing mean amplitude represents a considerable change in the characteristics of fluidization, perhaps reducing the uniformity of fluidization.

From Fig. 6, the mean amplitude begins to decrease as the static bed height increases above 2 H/D. Traditionally, the bubble has a longer residence time in a higher bed, and may coalesce with other bubbles, increasing the mean amplitude. However, these results

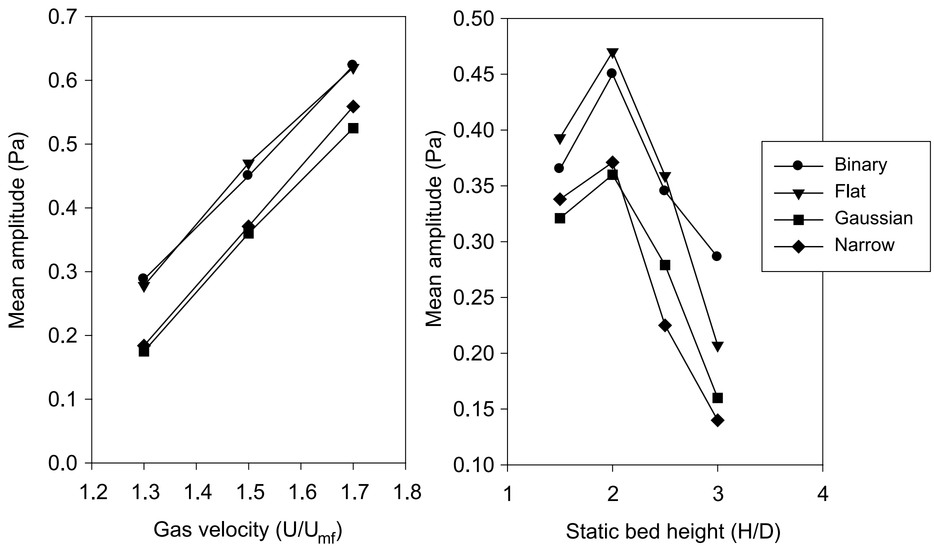

Fig. 6. Mean amplitude of pressure at different gas velocity and static bed height.

reveal that the bubble does not coalesce with other bubbles to form a large bubble. The plastic combustion process may affect the behaviors of bubble. Wey and Chang (1995) considered that the plastics crack to generate organic vapor, when the organic component reaches a particular concentration, the volatiles explode to cause the pressure to changing suddenly. The volatiles explode to destroy the coalesced bubbles, and form small bubbles again, which may decrease the mean amplitude.

3.3. Skewness and flatness

Skewness and flatness can be used to measure the extent of symmetry and sharpness in the probability density function about the mean value. When the pressure fluctuations are normally distributed, the skewness is 0 and the flatness is 3. Comparing the normal distribution and variations of skewness and flatness at the same standard deviation reveals that the skewness is positive or negative according to the direction of asymmetry about the mean value. The flatness is larger or smaller than three, according to the extent of the sharpness about the mean value (Lee and Kim, 1988). Flatness and skewness are measured by these functions.

$$S = \frac{1}{\sigma^3} \int_{-\infty}^{+\infty} (x - \bar{x})^3 f(x)\,\mathrm{d}x \tag{3}$$

$$F = \frac{1}{\sigma^4} \int_{-\infty}^{+\infty} (x - \bar{x})^4 f(x)\,\mathrm{d}x \tag{4}$$

Fig. 7 shows the measured skewness. The skewness increases with the gas velocity, but decreases as static bed height increases. Comparing the skewness with the mean amplitude and the dominant frequency reveals that the volatile substances explode during plastic combustion, destroying the periodic bubble behavior. The coalescence of bubbles, breakdown of bubbles and explosion of volatile substances occur simultaneously, causing the pressure fluctuations to change suddenly and influence behaviors of fluidization.

Fig. 8 presents the value of flatness. As the gas velocity increases, the flatness decreases, showing that the fluidization is regulated. However, the flatness increases with the static bed height, implying that the signal distribution of pressure from convergence to width. This result is consistent with the skewness, implying that the pressure fluctuations to change suddenly.

3.4. Fluidized index

In order to describe whether bed behavior is good or bad, Morse and Ballou (1951) provided a uniformity index to evaluate numerically the uniformity of fluidization. Shuster and Kisliak (1952) modified this index for pressure fluctuations. The fluidization index is given by

$$\text{Index} = \frac{2\sqrt{2}\delta_{\mathrm{p}}}{\pi f_{\mathrm{p}}} \times 100 \tag{5}$$

Shuster and Kisliak (1952) also pointed out that the uniformity of fluidization is good when the index is less than 5. If the fluidization index exceeds 5, then the uniformity of fluidization is poor. Fig. 9 shows that the index decreases as the bed height increasing, improving

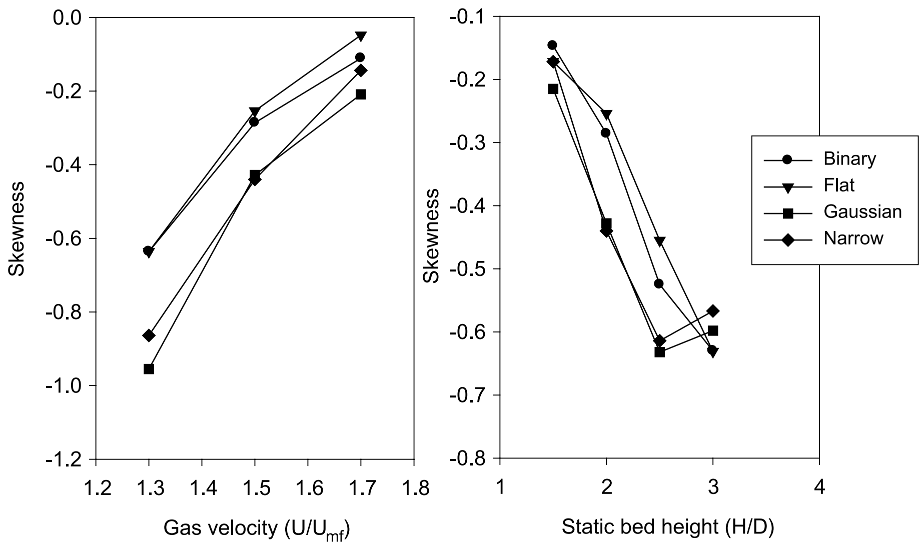

Fig. 7. The skewness of pressure at different gas velocity and static bed height.

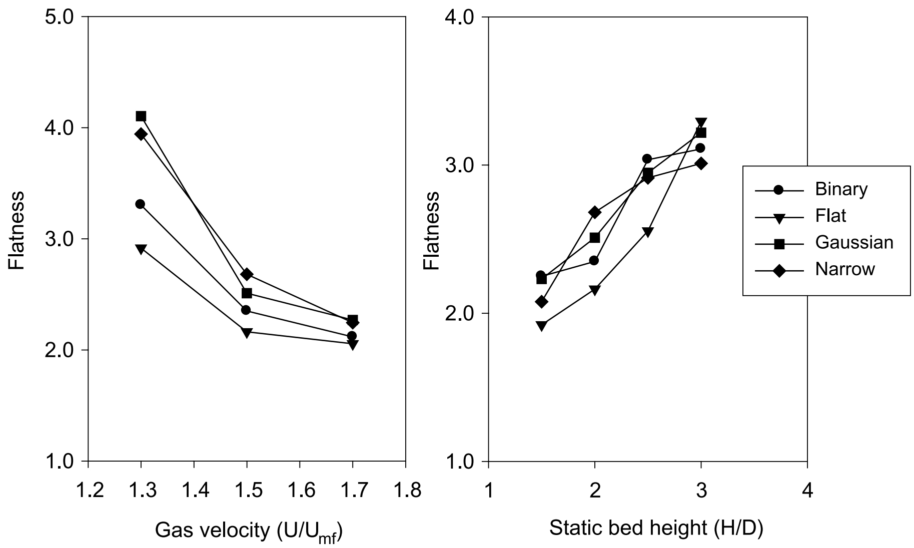

Fig. 8. The flatness of pressure at different gas velocity and static bed height.

the behavior of fluidization. According to the dominant frequency and the skewness, increasing bed height increases the sources of pressure and decreases the period of bubble, which changes are bad for fluidization. However, these changes of fluidization do not decrease the efficiency of combustion. Among the results of statistical analysis and power spectral analysis, the mean amplitude and fluidized index vary in the same way with the concentration of organic pollutants. Therefore, these two indices can be used to assess the efficiency of combustion.

3.5. Comparison of organic pollutants by statistical and power spectral analysis under various conditions

3.5.1. Static bed height (H/D)

Fig. 4 plots the concentration of organic pollutants for different static bed heights. Comparing the statistical analysis and power spectral analysis with organic concentration shows that the mean amplitude (Fig. 6) and fluidized index (Fig. 9) vary similarly with the organic concentration, implying that the generation of organic pollutants is strongly related to the mean amplitude and

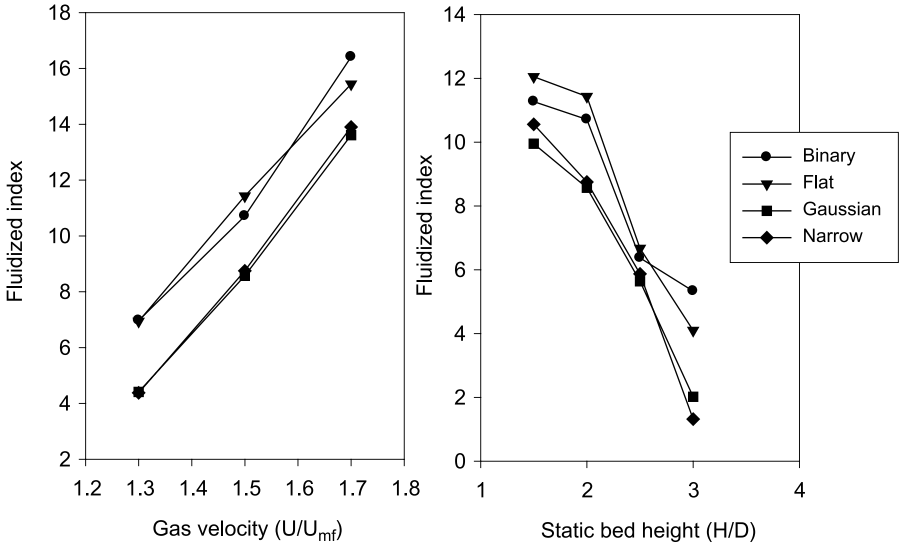

Fig. 9. Fluidized index of pressure at different gas velocity and static bed height.

the fluidized index. According to the preceding discussion, the sources of pressure fluctuation increases and the fluidization passes through bad periods, causing the uniformity of fluidization to decrease as the bed height increases. However, the organic concentration does not increase with bed height, which result is not as expected. Other investigators (Rasul et al., 1999, 2000; Rasul and Rudolph, 2000) stated that when a system of binary particles with various sizes and densities is fluidized, the behaviors of different particle tend to segregation. The large particle primarily feeds at top layer, while the other particles stay at the bottom layer of the bed. As the gas velocity is increased, the gradual inversion of layers is observed. Larger particles that originally stay on the top will become segregated at the bottom of bed. Consequently, the plastic may fall gradually to the bottom during combustion. The organic pollutants, which are cracked from the plastic surface have a long residence time during which they contact bed materials. The inversion of layers will promote combustion efficiency and thus reduce the concentration of pollutants.

According to the dominant frequency, the skewness and the flatness, the signal of pressure fluctuations gradually distributed extensively as bed height increases. Traditionally, a rising bubble has a longer residence time in a higher bed and may coalesce with other bubbles while rising. At a low gas velocity, the oxygen in a large bubble is not exchanged with the outside. The oxygen concentration declines to reduce the efficiency of combustion. However, Wey and Chang (1995) found that in the combustion of plastics, the surface of the plastics firstly swales and cracks to generate organic vapor. When the organic component reaches a particular concentration, the volatile substances explode and the plastic begins to combust. The volatiles explode, causing the pressure in the combustion chamber to change suddenly, destroying the coalescent bubbles to form small bubbles again, possibly increasing the exchange of oxygen. Although the gas explosion causes the pressure to change and reduce the period of bubble. These behaviors will decrease the efficiency of reaction in the operating of fluidized bed. However, in fluidized incineration the efficiency of conversion of oxygen between bubbles and wastes rises, increasing the combustion efficiency and reducing the concentration of organic pollutants.

3.5.2. Gas velocity (U/U_{mf})

According to the two-phase theory of fluidized bed, bubble size increases as gas velocity increases, when the operating gas velocity exceeds the minimum fluidization velocity. Meanwhile, the residence time of gas and oxygen conversion efficiency is decreased. Accordingly, Fig. 4 plots the increase of the concentration of organic pollutants with gas velocity. The mean amplitude (Fig. 6) and fluidized index (Fig. 9) have similar tendency. These results indicate that the uniformity of fluidization decreases as gas velocity increases.

Figs. 7 and 8 plot skewness and flatness, the skewness increases with gas velocity, while the flatness decreases. These findings show that the pressure fluctuations have high periods and distribute from width to convergence. The effect of plastic combustion on the exchange of oxygen between bubbles and the emulsion phase becomes weaker as the gas velocity increases. Consequently, the residence time associated with gas and oxygen transfer, decreases, increasing the concentration of organic pollutants.

3.5.3. Particle size distribution (PSD)

According to statistical analysis and power spectral analysis, four PSDs exhibit similar tendencies of pressure distribution. However, for mean amplitude, flatness and fluidized index reveal that the four PSDs can be divided into two groups. The Gaussian and narrow distributions belong to one group and the binary and flat distributions belong to the other. The mean amplitudes and fluidized indices of the Gaussian and narrow distributions are smaller than those of the binary and flat distributions, implying that the uniformity of fluidization of the Gaussian and narrow distributions is higher than that of the binary and flat distributions. The concentrations of organic pollutants generated with Gaussian and narrow distributions are lower than that generated with the other distributions.

Gauthier et al. (1999) indicated that the fluidization behavior of the binary and flat distributions tends to segregation. Therefore, the plastics do not mix completely with the sand bed and appear segregated, reducing the efficiency of combustion. The narrow distribution reduced defluidization and segregation, enhancing the stability of operation. The efficiency of combustion of the narrow distribution is better than that of other distributions. For a Gaussian distribution, the extreme-sized particles represent a small proportion of all particles, so the behavior of the Gaussian distribution was similar to that of the narrow distribution. Consequently, the fluidization with the narrow and Gaussian distributions is uniform, yielding greater mass and heat transfer and a related decrease in organic pollutants. The bed materials should maintain narrow or Gaussian distributions to keep high combustion efficiency during incineration.

4. Conclusion

This work elucidates the effect of hydrodynamic parameters of fluidization on the generation of organic pollutants (BTEXs and PAHs) during incineration. The relevant hydrodynamic parameters include PSD of bed materials, the static bed height and the gas velocity. To measure the pressure fluctuations during incineration, statistical analysis and power spectral analysis are used to assess the relationship between uniformity of fluidization and the generation of pollutants in a fluidized bed incinerator.

In general, the reaction efficiency will reduce with the uniformity of fluidization declining in the fluidized bed reactor. However, the concentration of organic pollutants does not increase with uniformity of fluidization decreasing, which result is not as expected. It may be that the explosion of the volatiles causes the pressure in the combustion chamber to change suddenly and destroy the coalescent bubbles to form small bubbles again. The gas explosion possibly increases the efficiency of conversion of oxygen between bubbles and wastes, increasing the combustion efficiency and reducing the concentration of organic pollutants.

Among the results of statistical analysis and power spectral analysis, the mean amplitude and fluidized index similarly vary with the concentration of organic pollutants. These two indices can be used to assess the efficiency of combustion. The mean amplitude and the fluidized index show that the four PSDs can be divided into two groups. The Gaussian and narrow distributions belong to one group and the binary and flat distributions belong to the other. The uniformity of fluidization with Gaussian and narrow distributions is better than that of the binary and flat distributions. The concentration of organic pollutants was generated using Gaussian and narrow distributions are also lower than that generating by other distributions. Consequently, the bed materials should be maintained with narrow or Gaussian distributions to maintain a high combustion efficiency during incineration.

Acknowledgements

The authors would like to thank the National Science Council of the Republic of China, Taiwan for financially supporting this research under Contract No. NSC 91-2211-E-005-012.

References

Arena, U., D'Amore, M., Massimilla, K., 1983. Carbon attrition during the fluidized combustion of a coal. AIChE J. 29, 40–49.

Arion, A., Baronnet, F., Lartiges, S., Birat, J.P., 2001. Characterization of emissions during the heating of tyre contaminated scrap. Chemosphere 42, 853–859.

Bemrose, C.R., Bridgwater, J., 1987. A review of attrition test methods. Powder Technol. 2, 97–126.

Chiang, P.C., You, J.H., Chang, S.C., Wei, Y.H., 1992. Identification of toxic PAH compounds in emitted particulates from incineration of urban solid wastes. J. Hazard. Mater. 31, 29–37.

Chirone, R., D'Amore, M., Massimilla, M., Mazza, A., 1985. Char attrition during the batch fluidized bed combustion of a coal. AIChE J. 31, 812–820.

Durlak, S.K., Biswas, P., Shi, J., Bernhard, M.J., 1998. Characterization of polycyclic aromatic hydrocarbon particulate and gaseous emissions from polystyrene combustion. Environ. Sci. Technol. 32, 2301–2307.

Fan, Z., Chen, G.T., Chen, B.C., Yuan, H., 1990. Analysis of pressure fluctuations in a 2-D fluidized bed. Powder Technol. 62, 139–145.

Gauthier, D., Zerguerras, S., Flamant, G., 1999. Influence of the particle size distribution of powders on the velocities of minimum and complete fluidization. Chem. Eng. J. 74, 181–196.

Griest, W.H., Tomkins, B.A., 1986. Influence of carbonaceous particles on the interaction of coal combustion stack ash with organic matter. Environ. Sci. Technol. 20, 291–295.

Gulyurtlu, I., Karunaratne, D.G.G.P., Cabrita, I., 2003. The study of the effect of operating parameters on the PAH formation during the combustion of coconut shell in a fluidized bed. Fuel 82, 215–223.

He, Z., Zhang, W., He, K., Chen, B., 1997. Modeling pressure fluctuations via correlation structure in a gas–solids fluidized bed. AIChE J. 43, 1914–1920.

Kai, T., Furusaki, S., 1985. Behavior of fluidized beds of small particles at elevated temperatures. J. Chem. Eng. Jpn. 18, 113–118.

Lee, G.S., Kim, S.D., 1988. Pressure fluctuations in turbulent fluidized beds. J. Chem. Eng. Jpn. 21, 515–521.

Lee, S.C., Chiu, M.Y., Ho, K.F., Zou, S.C., Wang, X., 2002. Volatile organic compounds (VOCs) in urban atmosphere of Hong Kong. Chemosphere 48, 375–382.

Leu, L.P., Lan, C.W., 1990. Measurement of pressure fluctuations in two-dimensional gas–solid fluidized bed at elevated temperatures. J. Chem. Eng. Jpn. 23, 555–562.

Lin, C.L., Wey, M.Y., You, S.D., 2002. The effect of particle size distribution on minimum fluidization velocity at high temperature. Powder Technol. 126, 297–301.

Morse, R.D., Ballou, C.O., 1951. The uniformity of fluidization its measurement and use. Chem. Eng. Prog. 47, 199–204.

Nam, W., Kim, J., Han, G., 2002. Photocatalytic oxidation of methyl orange in a three-phase fluidized bed reactor. Chemosphere 47, 1019–1024.

Pell, M., Williams, J.C., Allen, T. (Eds.), 1990. Handbook of Powder Technology. Elsevier, Amsterdam.

Rasul, M.G., Rudolph, V., 2000. Fluidized bed combustion of australian bagasse. Fuel 79, 123–130.

Rasul, M.G., Rudolph, V., Carsky, M., 1999. Segregation potential in binary gas fluidized beds. Powder Technol. 103, 175–181.

Rasul, M.G., Rudolph, V., Wang, F.Y., 2000. Particles separation using fluidization techniques. Int. J. Miner. Process. 60, 163–179.

Ray, Y.C., Jiang, T.S., 1987. Particle attrition phenomena in a fluidized bed. Powder Technol. 49, 193–206.

Sadasivan, N., Barreteau, D., Laguerie, C., 1980. Studies on frequency and magnitude of fluctuations of pressure drop in gas–solid fluidized beds. Powder Technol. 26, 67–74.

Shuster, W.W., Kisliak, P., 1952. The measurement of fluidization quality. Chem. Eng. Prog. 48, 455–458.

Sun, G., Grace, J.R., 1992. Effect of particle size distribution in different fluidization regimes. AIChE J. 38, 716–722.

Svoboda, K., Cermak, J., Hartman, M., Drahos, J., Selucky, K., 1983. Pressure fluctuations in gas-fluidized beds at elevated temperatures. Ind. Eng. Chem. Process Des. Dev. 22, 514–520.

Van Der Schaaf, J., Schouten, J.C., Van Den Bleek, C.M., 1998. Origin, propagation and attenuation of pressure waves in gas–solid fluidized bed. Powder Technol. 95, 220–233.

Wey, M.Y., Chang, C.L., 1995. Kinetic study of polymer incineration. Polym. Degrad. Stab. 48, 25–33.

Wey, M.Y., Chao, C.Y., Yu, L.J., 1996. The influence of heavy metal on PAH formation during incineration. Toxicol. Environ. Chem. 56, 35–45.

Wey, M.Y., Yan, J.T., Wei, M.C., 1998. The major species of heavy metal aerosol resulted from water cooling system and spray dryer system. J. Air Waste Manage. Assoc. 48, 1069–1076.

Wheatley, A.D., Sadhra, S., 2004. Polycyclic aromatic hydrocarbons in solid residues from waste incineration. Chemosphere 55, 743–749.

Zhang, X.J., 1998. The effect of the oxygen fraction on volatile organic-compound emissions from waste combustion. J. Environ. Sci. Health A 33, 147–163.