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Study on mixing performance of municipal solid waste (MSW) in differential density fluidized beds (FBs)

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Abstract

Mixing performances of municipal solid waste (MSW) in differential density fluidized beds (FBs) have been investigated simulating five kinds of materials (plastic, wood, candle, coal and coal-stone). The results show that the differential density FB technology can realize good mixing performances for different MSW components. The density of MSW components has a conspicuous effect on the mixing characteristics of FB. Also, the size of the components has effects. The mixing index is adopted via a regression analysis to the experimental data, and a mixing expression formula is obtained, that will be beneficial for MSW incinerator design and operation. © 2001 Published by Elsevier Science B.V.

Keywords: Municipal solid waste; Fluidized bed; Mixing performance; Incineration

1. Introduction

In view of long term and sustainable development, the goal of disposal of municipal solid waste (MSW) should be achieved with minimal effect on the environment and reduction of its quantity [1]. The MSW, in China, which has the variety characteristics of density, material size, moisture component and low heat value (usually <1000 kcal/kg), is mainly comprised paper, plastic, glass, metal, fabric, kitchen residue, rind, wood, stone, etc. There are several methods to treat MSW, such as land disposal, composting, incineration, etc. of which incineration technology appears to be the main method. However, because of the above characteristics of MSW, it is difficult to treat using incineration technologies, especially for the fluidized bed (FB) incineration system. The characteristics of MSW readily affect the stability of FB combustion if treated improperly in the bed as they can lead to the deterioration of fluidization and incomplete combustion.

Based on the characteristics of Chinese MSW, a differential density FB incineration technology has been developed in the Zhejiang University through a series of fundamental studies and pilot plant research and applied to a 150 t/day incinerator, built in Yuhang Cogeneration plant of Hangzhou City, which has been in operation since 1998.

The differential density FB is a system that is composed of different materials (for example, silicon sand as a basic bed material together with MSW) of large differential densities. The research shows differential density bed materials adopted in a differential density FB, can make materials appear in a certain mass distribution along the bed height and be effective in preventing big or heavy pieces of waste materials from settling out and preventing light waste components from floating on the bed surface. Waste materials distribute throughout the bed height and result in stable combustion.

Mixing experiments are conducted using materials to simulate waste components. In this investigation, tendency of sinking or floating and concentration distribution along the bed height of material in differential density bed under stable condition are observed. In addition, mixing performances for different MSW components are obtained in the FB. The mixing index is adopted to analyze and discuss the experimental data. A regressive analysis is used to handle the experimental data.

2. Theoretical analysis and experimental method

2.1. Theoretical analysis

Different sizes and densities of materials will lead to segregation in the operation of FB, but as long as this kind of segregation is not very serious, it will not bring any adverse effect on the combustion in the FB.

The research related to binary FB undertaken by Chiba et al. [2] indicates that the densities of MSW components have a more pronounced effects on their mixing

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Nomenclature

C_{hi}	distributed concentration of material at the height of h (kg m^{-3})
$\hat{C}_h$	relative distributed concentration of total material ($\sum C_{hi}/\sum C_{oi}$)
$\hat{C}_{hi}$	relative distributed concentration of material along the bed height (C_{hi}/C_{oi})
C_{oi}	even distributed concentration of material along the bed height (kg m^{-3})
$\hat{C}_u$	relative distributed concentration of particle in upper half part of fluidized area
$\hat{C}_l$	relative distributed concentration of particle in lower half part of fluidized area
d_m	average particle size of bed material particle (mm)
d_{si}	even particle size of simulating material particle (mm)
h	the distance from air distributor (m)
M_i	mixing index, ($M_i = 2\int_{1/2}^{1}\hat{C}_u/(\hat{C}_u+\hat{C}_d)\,dz - 1$)
N	the ratio of FB velocity to minimum fluidized velocity
R_d	relative particle size rate (d_{si}/d_m)
R_p	relative density (ρ_{si}/ρ_m)
ρ_m	density of basic bed material (kg m^{-3})
ρ_{si}	density of simulating material particle (kg m^{-3})

performances. The sizes of components have relatively less effects. If the fluidized bed velocity is above a certain critical value, the distribution conditions of the bed material is hardly affected by the operation bed velocity [3,4].

For mixing performance of the FB, a GR mathematical model was proposed by Gibilaro and Rowe [5] and modified by others [6–9]. The model assumes that bubbles have the predominant effect on mixing. The mixing performance is dependent on the density difference, between dense and dilute phases, recycling, exchange, segregation and diffusion. In contrast to the large number of published researches for mixing performance of the common FB, there are very few researches focusing on MSW FB incineration process.

Based on the above analysis, this research mainly focuses on mixing performances for different components of MSW in two aspects (density and particle size) and then discussing the basic principle underlying the process.

An approach based upon relative distributed concentration is adopted when various mixing materials are put into the FB. The relative distributed concentration of one kind of material $\hat{C}_{hi}$ is

$$\hat{C}_{hi} = \frac{C_{hi}}{C_{oi}} \tag{1}$$

And the relative distributed concentration of the total materials:

$$\hat{C}_h = \frac{\sum C_{hi}}{\sum C_{oi}} \tag{2}$$

When one kind of material is evenly dispersed in the whole FB, any site has the characteristic in the FB, $\hat{C}_{hi} = 1$.

For convenience, the mixing index (M_i) is introduced as the relative particle distributed concentration difference between the upper half part and the lower half part of FB. So M_i can be written as

$$M_i = \hat{C}_u - \hat{C}_l \tag{3}$$

or

$$M_i = \int_{1/2}^{1}\hat{C}_h\,dz - \int_{0}^{1/2}\hat{C}_h\,dz \tag{4}$$

$$\text{since,} \int_{0}^{1/2}\hat{C}_h\,dz = 1 - \int_{1/2}^{1}\hat{C}_h\,dz \tag{5}$$

$$\text{therefore,}\ M_i = 2\int_{1/2}^{1}\hat{C}_h\,dz - 1 \tag{6}$$

If $M_i = 0$, there is no difference between the two parts of the bed, and the material is completely mixed in FB.

If $M_i > 0$, the mass concentration of material is higher in the upper part of the bed and the material has the tendency to float.

If $M_i = 1$, all the materials float together. On the contrary, if $M_i < 0$, the mass concentration of material is concentrated in the lower part of the bed and the material has a tendency to sedimentation. If $M_i = -1$, all the material sinks together.

2.2. Experimental apparatus and method

The MSW is mainly composed of paper, plastic, metal-fabric, residue of kitchen, rind, wood, coal-ash, brick, etc. whose approximate densities are listed in Table 1. According to the above table, we generalize MSW into five main kinds of material and then five simulating materials are used to do research on mixing performances. In the experiment, plastic balls are adopted to simulate plastic material (including paper, plastic, etc.); wood chunks to simulate wood material (including wood, fabric, etc.); candle to simulate material of residue of kitchen which is composed of

Table 1
Densities of different MSW components

Material	Density (kg m^{-3})
Paper	691.7
Wood	646
Waste tire	1020
Plastic	1000
PVC pipe	1517.1
Brick	3000

Table 2
Bed material and characteristics of simulating particles

Bed material	Density ($kg\,m^{-3}$)	Particle size (mm)	
Silicon sand	2450	1.26	
Coal particle	1450	0.98	
Simulating MSW components	True density ($kg\,m^{-3}$)	Size (mm)	Shape
Wood	646	30, 20, 15, 10	Rectangular
Plastic ball	1000	5	Round
Candle	849	∅ 15 × 9.1	Cylindrical
Coal particle	1445	6, 8.5, 11, 13.5, 17.5	Approximately round
Stone	2056	6, 8.5	Approximately round

residue of kitchen, rind, etc.; coal particles to simulate hard plastic material (plastic package, PVC pipe, etc.); stone to simulate coal-stone material (including glass, coal-stone, etc.). The characteristic of different basic bed material and simulating particles are listed in Table 2. Research has been done with the experimental equipment in the Institute for Thermal Power Engineering, Zhejiang University. Fig. 1 shows the test bed of fluidized system whose cross-section size is 240 mm × 240 mm.

This FB equipment is divided into two parts (Sections 1 and 2) and the experiment is mainly done in the Section 2. The height of the bed (Section 1) is 400 mm, which is composed of side-and-face transparent glass and one-side iron plate. In the side of the iron plate, four equidistant slots were designed to allow a piece of iron plate to put in and out freely. It is kept airtight by seals and the bed is divided into five areas by the four iron plates.

The experimental method for determining mixing performances is to add bed material into the bed, then to evenly poured a certain amount of simulating particle (occupying 6–19 wt.%) on the surface of bed material. The blower is started and airflow rate is increased slowly until the bed is fully fluidized and then the condition is maintained for a certain time to enable the mixing to achieve stability. After the flow rate is noted, air blower is shut down, the bypass is opened and the plates are slid into the bed. The bed material and simulating particle are then collected by vacuum and the material concentration condition along the bed height is obtained by sieving and weighing the bed solids.

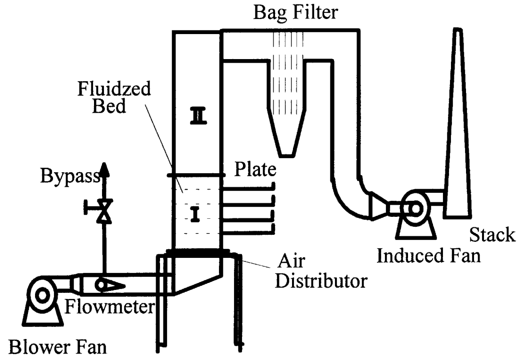

Fig. 1. Schematic of FB experimental apparatus.

3. Experimental results and analysis

Compared to silicon sand, which is used as bed material, MSW materials with heavy density and large size tend to sink down in the bottom of the FB under normal situation. This can destroy the normal fluidization operation. The major elements, affecting material distribution in differential density FB, are operation velocity, material density and size of the material.

3.1. *Effect of FB velocity on MSW mixing performances*

Fig. 2 shows the variation of material distribution condition in the FB at different FB velocities which presents operation gas velocity has an important effect on material distribution in the FB.

When the FB velocity is lower, segregation is more serious. Mixing quality can be improved by increasing the FB velocity. After the velocity reaches a certain numerical value, the material distribution generally tends to a stable condition, which is no longer affected by FB velocity. From the Fig. 2, if fluidized number N (the ratio of FB velocity to minimum fluidized velocity) reaches 2.3, the simulating material tends to a stable condition that is in the fully fluidized condition. All the following experiments were done under these conditions.

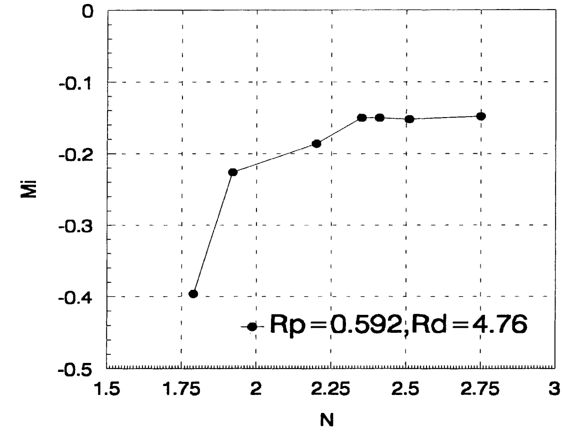

Fig. 2. Effect of FB velocity on the MSW mixing performance.

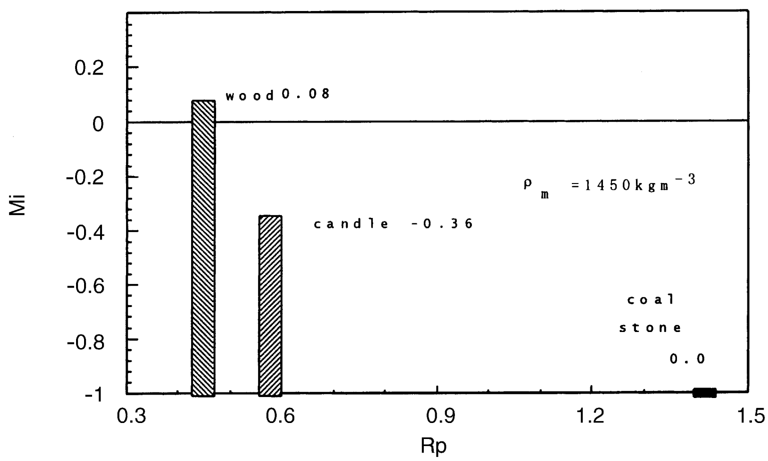

Fig. 3. Mixing performance of simulating components in the FB (bed material: coal).

3.2. *Effect of component density on MSW mixing performances in differential density FB*

Material density has a very important effect on the mixing performances in a differential density FB, when the fluidizing velocity was above a certain numerical value (e.g. fluidized number, $N > 2.3$). Primary experiments show that, as far as a single component is concerned, material with a low-density still had the tendency of floating in an FB while material with high-density sank.

Further experiments suggest that, if the relative particle size is almost constant, the results shown in Fig. 3 can be obtained when a material with relatively lower density (coal particle $d_p = 1450\,\mathrm{kg\,m^{-3}}$) is used as bed material. With a low-density bed material, formerly up-floating material which tended to float previously tends to an even mixing condition with the increase of relative density; that is to say, M_i tends to be "0". But a high-density material such as coal-stone basically tends to sink down, so it is improper to unilaterally seek to use a relative low-density ratio of MSW to bed material, as this will lead to heavier particles sinking to the bottom of the bed.

In this study, heavy metal materials have been ignored, because, for example, iron particles (d_p is about $7800\,\mathrm{kg\,m^{-3}}$) cannot be fluidized in the usual FB. If the MSW should include heavy metal materials, these will settle down to the bottom of the FB.

In order to improve situation, as mentioned above, a high-density bed material was used in the mixing experiments. Results shown in Fig. 4 are obtained in the fluidized condition in which silicon ($d_p = 2450\,\mathrm{kg\,m^{-3}}$) is taken as bed material. In the experiment, the mass-density of initial components was assumed to be the same and the components were evenly distributed in the FB. For this condition, both the low-density and high-density components were distributed evenly in the FB with little tendency for material either to float or to sink so that the mass distributed concentration of the total components tended to be even. In fact, the mixing index under these conditions was about between −0.2 and −0.1 meaning that there was a slight tendency towards sinking in the bed.

3.3. *Effect of component size on MSW mixing performances in the FB*

It is found that the effect of component size has a good relationship with its density. As for low-density MSW components ($d_p < 1000\,\mathrm{kg\,m^{-3}}$), changing the size of the components has some effect on their mixing performances in the bed material. Compared to the effect caused by the material density, the effect caused by the material size is more important. When the relative size of wood is increased from 12 to 24, the mixing index reduces slightly; that is, the wood has a tendency to sink in the FB as shown in Fig. 5.

For relatively high-density components such as hard rubber, brick, etc., the effect of component size is different. Take the coal and the coal-stone distribution illustrated in Figs. 6 and 7 as examples. Increasing the size will cause

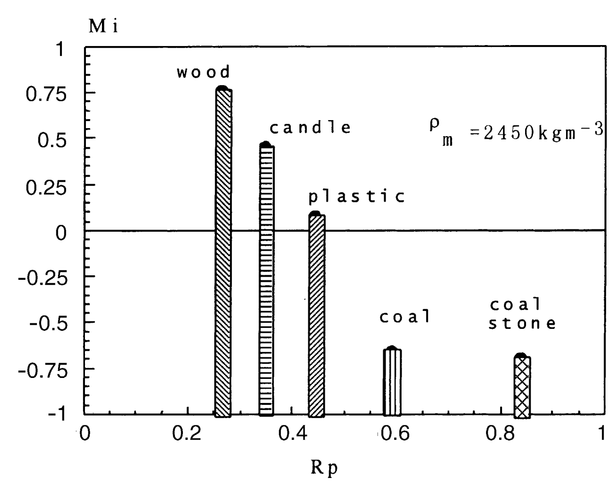

Fig. 4. Mixing performance of simulating components in the FB (bed material: silicon).

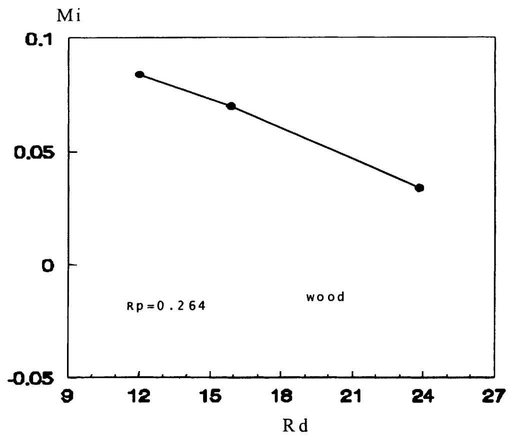

Fig. 5. Effect of wood size on the mixing performance in the FB (bed material: silicon).

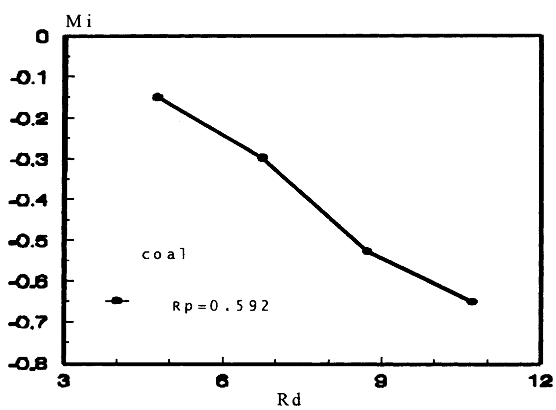

Fig. 6. Effect of coal size on the mixing performance in the FB (bed material: silicon).

the material to have a tendency to sink. The relative size of these kinds of components should be <12.

When adopting the differential density FB to dispose of, MSW has an ability to handle low-density MSW components, which reduces the demand for pretreatment of the MSW. For high-density MSW components, the relative

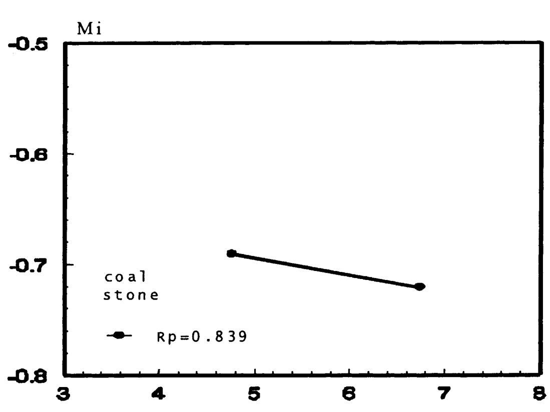

Fig. 7. Effect of coal-stone size on the mixing performance in the FB (bed material: silicon).

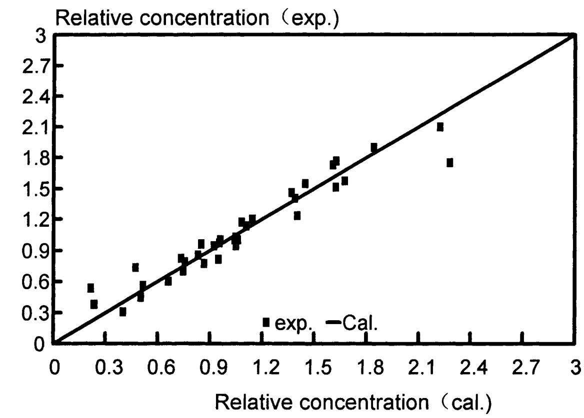

Fig. 8. Comparison of experimental results with calculated results.

particle size should be <12. In fact, this relative particle size can be enlarged to some extent and can still keep normal operation by adapting the differential density FB to combine with inner circulating bed.

3.4. Experimental results and regressive analysis

Regression analysis of experimental data leads to

$$M_{\rm i} = 3.09 \times [0.55\,{\rm e}^{-(R_{\rm d}-1)/3} - R_{\rm p} + 0.45] + 0.028,\quad M_{\rm i} \in (-1, 1). \tag{7}$$

The error between the relative distributed density of material $\hat{C}_{\rm h}$ obtained schematically and calculation was within 20% as shown in Fig. 8.

In practical applications, the material mixing in an FB can be evaluated by formula (7) using the relative particle size and the relative density of a differential density FB system.

4. Conclusion

In the paper, simulating materials were used to do research on the mixing performance of different MSW components in a differential density of FB. This study shows that material density has an important effect on material distribution in the FB among all the factors. Adopting a bed material with a high-density will be a benefit to the mixing of MSW components in the bed and mixing index is about between −0.2 and −0.1. When relative density is almost constant, material particle size has an effect which is relatively less than that of material density on the distribution in the bed. The mixing index is adopted via a regression analysis to the experimental data, and a mixing expression formula is obtained, that will be beneficial for MSW incinerator design and operation.

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