Application of CFB (Circulating Fluidized Bed) to Sewage Sludge Incinerator

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CFB (Circulating Fluidized Bed) is widely used for coal-fired boilers. For combusting sewage sludge in CFB, a suitable fluidization mode for damp material is required. Experiments for combusting sewage sludge were carried out using a pilot-scale CFB incinerator. As a result, a desirable combustion method was established by optimizing the fluidization mode and controlling the profiles of the temperature and pressure. The results indicated that CFB is applicable to sewage sludge incineration.

1. Introduction

In line with the development of sewage systems, sewage sludge is now being generated in Japan at a rate of approximately 2 million tons per year (equivalent solid substance weight). Most of this sludge is subjected to volume-reducing treatment by incineration after de-watering. Sewage sludge cake obtained by de-watering is a damp substance that has a high water content of 70 to 85%. Bubbling fluidized bed incinerators are generally used for incinerating sewage sludge cake because this type of incinerator enables stable combustion with a relatively simple structure[1].

In the past several years, Japanese manufacturers of sewage sludge incinerators have proposed applying CFB (Circulating Fluidized Bed) for incinerating sewage sludge cake. CFB incinerators have a higher gas velocity (4-6 m/s) inside the furnace compared to the bubbling fluidized bed incinerators and allows the height of the combustion zone to be raised. Therefore, it is possible to obtain a higher combustion load per unit horizontal cross section, which reduces the construction area required for installing the furnace. Further, combustion air is supplied in two stages: primary air (fluidizing air) and secondary air, and so the power load of the fluidizing blower is reduced. Two-stage combustion is also expected to lower the environmental impact. Bubbling fluidized bed incinerators have a drawback in that agitation and mixing in the combustion chamber are hindered when the furnace size is increased. In contrast, even large-size CFB incinerators are expected to maintain excellent combustion because sufficient agitation and mixing are carried out by high-velocity fluidization.

In CFB combustion, part of the bed material and unburned char carried out from the top of the riser (combustion chamber) are captured by the cyclone and circulated through the system, and are completely combusted. Therefore, it is most suitable for combusting coal that contains much fixed carbon and hence it is widely applied to coal-fired boilers. In contrast, sewage sludge cake has a high water content and in many cases, its solid portion contains volatile matters of nearly 70%. The properties are significantly different from those of coal, and so different fluidization and combustion technologies are required when applying the same CFB technology to sewage sludge cake. The general properties of coal and sewage sludge are compared in **Table 1**.

NKK carried out a series of experiments using a CFB pilot plant that has a riser of inner diameter of 300 mm and height of 12m. It was confirmed that the CFB furnace is satisfactory for incinerating sewage sludge cake. The results are summarized below.

Table 1 Properties of coal and sewage sludge cake

		Bituminous coal	Sewage sludge cake
Moisture	%	0～8	70～85
Volatile matter	dry-%	13～40	50～75
Fixed carbon	dry-%	75～85	8～10
Ash	dry-%	2～5	15～40
Low heating value	MJ/kg	20～25	0.4～2.5

2. Experimental setup and conditions

Fig.1 is a flow diagram of the pilot plant used for the experiments. **Photo 1** is its exterior view. The CFB section is composed of a riser that works as a combustion chamber, a hot cyclone that captures circulating particles, a loop seal that prevents back-flowing of unburned gas from the furnace bottom, etc. The pilot plant also has a flue gas treatment section. The riser has the inner diameter of 300 mm and the height of 12 m and is lined by refractory. It is composed of a wind box, a distributor with primary air feed nozzles, secondary air injection ports, a sewage sludge cake feeder, an oil gun for feeding auxiliary fuel (kerosene), etc. Primary air is supplied from the wind box into the riser through the distributor. The bed material (fluidizing particles) is blown up from the bottom of the riser by primary air and secondary air. Sewage sludge cake is rigorously agitated and mixed with the bed material, dried, and burned. Part of the bed material and unburned char carried out from the top of the riser are captured by the cyclone as circulating particles, and returned back to the riser through the loop seal. Combustion flue gas discharged from the cyclone is cooled down by the gas cooler and dust contained in it is removed by the bag filter. The flue gas is then drawn out by the IDF (Induced Draft Fan), and discharged from the stack.

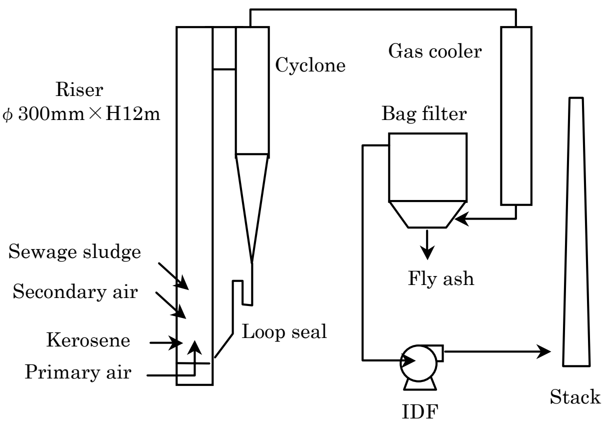

Fig.1 Pilot plant diagram

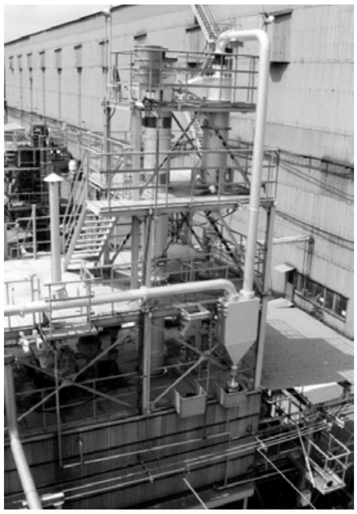

Photo 1 Pilot plant

Four types of sewage sludge cake were used in the experiments. **Table 2** shows their properties. Each of the four types of sewage sludge cake has the following characteristics.

A: Sewage sludge cake generated at a municipal sewage treatment plant. It has a comparatively low water content and high heating value.

B: Sewage sludge cake from wastewater including industrial origins. Its solid portion has a high oxygen content.

C: Digested sewage sludge cake that has a high ash content and extremely low heating value. Its solid portion has a high sulfur content.

D: Sewage sludge cake from a local mid- to small-scale municipality that has a high water content. Its solid portion has a high nitrogen content.

Table 2 Properties of sewage sludge cake

Sewage sludge cake		A	B	C	D
Moisture	%	76.6	78.8	80.1	84.9
Ash	dry%	17.5	19.9	40.3	15.0
Combustibles	dry%	82.5	80.1	59.7	85.0
High heating value	MJ/dry–kg	19.7	19.2	13.3	20.2
Low heating value	MJ/kg	2.3	1.8	0.4	0.7
C	dry%	44.3	42.5	31.1	44.9
H	dry%	6.2	6.1	4.8	6.4
N	dry%	5.3	4.4	4.5	8.3
O	dry%	26.0	26.5	18.1	24.6
S	dry%	0.7	0.6	1.3	0.8

Table 3 shows the experimental conditions. In the experiments, silica sand (major constituent: SiO_2) was used as the bed material. The air ratio was approximately 1.3. Primary air was supplied at the temperature of around 400°C, and secondary air at around 200°C.

Table 3 Experimental conditions

Sewage sludge feed rate	kg/h	40～60
Kerosene feed rate	L/h	13～19
O_2 (Cyclone ext.) in flue gas	%	4.4～5.4
Bed material diameter d_{P50} (Silica sand)	mm	0.13～0.30
Superficial gas velocity (800℃)	m/s	4.4～5.6

3. Results and discussion

3.1 Investigation on fluidization mode

As an operational guideline for CFB furnace, a fluidization mode most suitable for each type of material to be burned needs to be established; in other words, it is necessary to investigate what type of fluidizing state is to be formed in each zone of the riser[2]. First, an optimum fluidization mode for sewage sludge cake, which is characterized by a high water content, was studied.

When sewage sludge cake is charged into the riser, first it is necessary to fully evaporate its water content and dry it out in the lower zone of the riser. To do this, a dense bed must be formed in the lower zone of the riser below the secondary air injection port. Here, the dense bed means a zone that has a high particle density of the bed material and is in a fluidizing state where the gas velocity is low as in the conventional bubbling fluidized bed furnace. In contrast, in the upper zone of the riser above the secondary air injection port, it is necessary to completely combust the gas formed in the dense bed zone and unburned combustible matters contained in the dried sewage sludge cake. To do this, it is considered desirable to form a high-velocity fluidizing state in the upper zone and promote thorough agitation and mixing.

Suitable conditions for particle sizes of the bed material and allocation between primary air and secondary air were investigated to realize these states in the riser. As an example, **Fig.2** shows the results obtained when sewage sludge cake A was used. This figure shows the pressure profile along the height of the riser. The values were made dimensionless using the following equation and allocating unity to the value at the bottom of the riser (immediately above the distributor) and zero to the value at the top of the riser.

$$P' = (P - P_1)/(P_0 - P_1)$$

Where, P: Pressure at each measuring point, P_1: Pressure at the top of the riser, and P_0: Pressure immediately above the distributor.

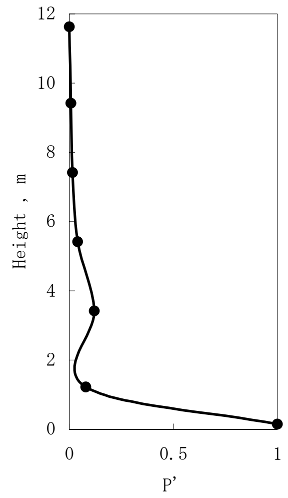

Fig.2 Pressure profile in riser

The lower zone of the riser has a high pressure, which indicates that a dense bed with a high particle density is formed there. The zone up to the height where P' is 0.2 in the above equation was defined to be a dense bed zone. Above this dense bed zone with hights over 2.0m, the pressure slightly increases with the hight due to the secondary air injection. After this slight increase, the pressure gradually decreases toward the top of the riser, which indicates that the upper zone is in a high-velocity fluidizing state.

This fluidization mode was judged to be the optimal one for combusting a damp substance, and its combustion characteristics were investigated as follows.

3.2 Optimization of dense bed zone

In order to maintain the combustion of a damp substance in the CFB furnace, it is necessary to promote primary combustion in the dense bed zone while vaporizing the water content. In doing so, it is extremely important to maintain the temperature of the dense bed zone above the temperature that can maintain the combustion.

The dense bed temperatures were measured while combusting sewage sludge cake A under identical conditions except that the ratio of primary air to secondary air was varied. **Fig.3** shows the results. The primary air ratio shown on the horizontal axis is the ratio of the primary air to the total amount of air required for combusting both sewage sludge cake and kerosene fed into the riser. The figure indicates that the highest dense bed temperature is obtained when the primary air ratio is 0.6. When the primary air ratio is increased further, the dense bed temperature decreases, which is considered to occur because the heat generated by the combustion of the sewage sludge cake and auxiliary fuel tends to move upward in the riser. Another probable cause of the temperature decrease is that the heat capacity in the lower zone of the riser is lowered because the particle density decreases as the gas velocity increases. Conversely, when the primary air ratio is decreased from 0.6, the minimum combustion required for maintaining the temperature is no longer carried out and hence the dense bed temperature decreases.

The primary air ratio determines the conditions in the early stage of combustion and therefore affects the flue gas properties. **Fig.4** shows the results of measuring the CO concentration at the exit of the cyclone when the plant was operated under the same conditions as in **Fig.3**. The CO concentration decreases with decreasing the primary air ratio. The probable cause is that a suitable thermal decomposition of the sewage sludge cake occurs in the dense bed zone, and combustible constituents generated there undergo complete combustion in the upper zone above the secondary air injection port. All types of sewage sludge cake indicated almost identical trends.

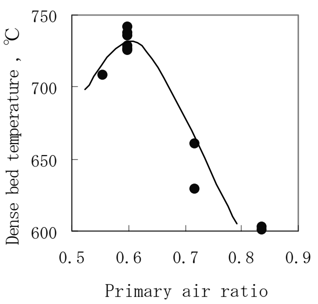

Fig.3 Influence of primary air ratio on dense bed temperature

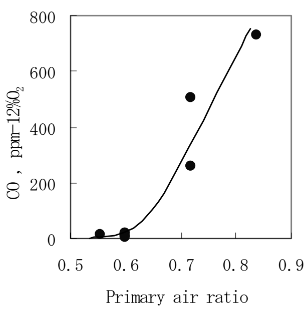

Fig.4 Influence of primary air ratio on CO emissions

Photo 2 shows the state of the dense bed zone photographed by a CCD camera when sewage sludge cake A was combusted at the primary air ratio of 0.6. The black spherical substances are sewage sludge cakes. The photograph indicates that stable combustion is maintained in the dense bed zone.

From the above, it was concluded that the optimum primary air ratio for the CFB furnace is around 0.6.

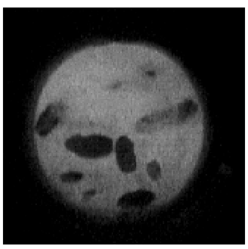

Photo 2 State of dense bed zone

3.3 Combustion characteristics in entire zone of riser

Combustion characteristics in the entire zone of the riser were investigated. **Fig.5** shows the profiles of the oxygen concentration and temperature in the riser when sewage sludge cakes A and D were combusted. It is clear that the oxygen supplied by the primary air is almost completely consumed in the dense bed zone below the secondary air injection port, and a reducing atmosphere is formed. The temperatures in this zone are comparatively low at 700 to 800°C, and it is considered that the water content in the sewage sludge cake is evaporated and combustible matters are gasified there. Above the secondary air injection port of the height of around 2 m, oxygen is gradually consumed with increasing height. The temperatures in this zone are around 850°C. This is probably because combustible matters gasified in the dense bed zone undergo complete combustion in the wide zone above the secondary air injection port, and a sufficiently wide high-temperature field is formed there.

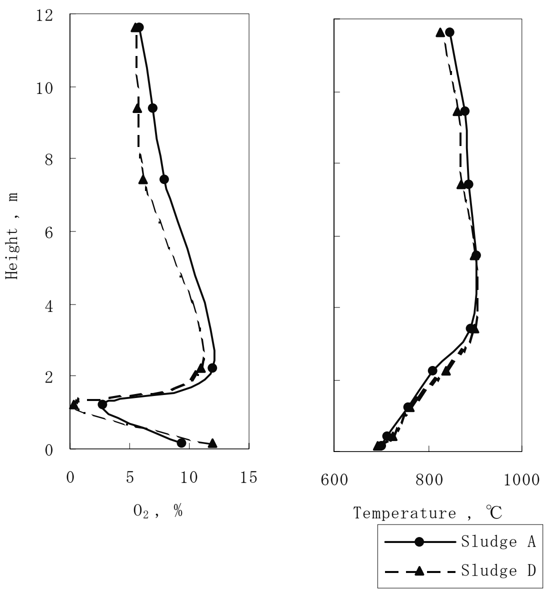

Fig.5 Profiles of O_2 and temperature in riser

3.4 Flue gas properties

Sewage sludge cake contains a higher nitrogen content compared to municipal solid wastes or plastic wastes. Hence, NOx and N_2O concentrations in the flue gas discharged to the atmosphere are serious concerns. Since CFB furnace has a higher gas velocity in the furnace compared to bubbling fluidized bed furnace, incomplete combustion due to a shorter gas residence time is another concern. Therefore, we investigated how to reduce the emissions of various harmful gases. **Table 4** shows properties of flue gas measured at the exit of the cyclone.

Table 4 Properties of flue gas from cyclone exit

Sewage sludge		A	B	C	D
O_2	%	5.3	5.1	5.0	4.4
CO	ppm–12%O_2	27	17	8	17
CO_2	%	11	10	12	10
NOx	ppm–12%O_2	48	65	31	54
N_2O	ppm–12%O_2	38	–	–	62
DXNs	ng–TEQ/Nm^3	0.00028	–	–	–

All of CO, NOx, and N_2O emissions from every type of sewage sludge cake were suppressed to low levels at the air ratio of approximately 1.3. The reasons for the reduction of each of these emissions were as follows:

(1) NOx

When sewage sludge cake is combusted in the fluidization mode as described above, nitrogenous compounds are turned into NH_3, HCN, etc. in the dense bed zone that has a reducing atmosphere. They then undergo complete combustion in the upper zone where secondary air is injected. This two-stage combustion helps reduce the NOx concentration.

(2) N_2O

When the furnace has the temperature profile as described above, N_2O is decomposed in the sufficiently wide high-temperature field in the upper zone of the riser. Therefore, it becomes possible to simultaneously reduce both NOx and N_2O, which are generally considered to have a tradeoff relation with regard to their emission behaviors[3),4)].

(3) CO

The gas in the upper zone of the riser is fully agitated and mixed, and undergoes complete combustion in the high-temperature field that spans the wide area in this zone. Therefore, the CO emissions are suppressed.

(4) Dioxins

These also undergo complete combustion in the high-temperature field that spans the wide area in the upper zone of the riser. Therefore, the dioxins emissions are suppressed to extremely low levels.

3.5 In-furnace desulfurization

Sewage sludge cake contains a higher sulfur content than municipal solid wastes and plastic wastes, and tends to emit a high concentration of SOx when incinerated. Therefore the flue gas is usually passed through a desulfurization scrubber that uses caustic soda (NaOH) solution before being released from a stack.

Since CFB furnace provides a high contact efficiency between the bed material and gas, desulfurization absorbents such as limestone (major constituent: $CaCO_3$) charged directly into the furnace are expected to perform desulfurization effectively. This method has been already used for coal-fired boilers. This method does not need flue gas desulfurization and associated wastewater treatment and helps reduce space and running costs. However, CaO generated by decomposition of limestone works as a catalyst for forming NOx from NH_3, and might have adverse effects on the NOx concentration, depending on the combustion conditions.

Experiments of in-furnace desulfurization were carried out under various conditions. Limestone was charged into the riser at the Ca/S molar ratio of 3.0 to 4.5 while sewage sludge cakes A, B, and C were combusted at the air ratio of approximately 1.3. A desirable temperature for a desulfurizing reaction by using limestone is thought to range from 800 to 850°C. In the riser, this temperature zone corresponds to the zone above the secondary air injection port, as shown in **Fig.5**. In order to fluidize the limestone in this zone and promote the reaction, pulverized limestone was used. **Table 5** shows the results.

Table 5 Results of de-SOx experiment

Sewage sludge		A	B	C
Molar ratio (Ca/S)	–	3.0	4.5	4.2
SO_2 (Estimated*)	ppm–12%O_2	134	81	123
SO_2 (Measured)	ppm–12%O_2	1.9	4.2	2.3
SO_2 removal	%	98.6	94.8	98.1
NOx	ppm–12%O_2	44	66	31

*Conversion ratio=100%

For each type of sewage sludge cake, it was found that more than roughly 95% of SO_2 is removed out of the estimated SO_2 concentration (*) that would have been emitted if all the sulfur in the sewage sludge cake had been converted to SO_2 (conversion ratio=100%). Further, the NOx concentration that posed a concern was almost at the same level as when in-furnace desulfurization was not performed.

Thus, it was proved that in-furnace desulfurization in the CFB can achieve a high efficiency without affecting the NOx concentration.

3.6 Leaching test of fly ash and bed material

Fly ash captured by the bag filter and bed materials extracted from the riser were subjected to leaching tests. **Table 6** shows the results. For all types of sewage sludge cake, no leaching of hazardous substances from fly ash or bed material was detected.

Table 6 Results of leaching test for fly ash and bed material

		Fly ash						Bed material		
Sewage sludge		A	A + Lime–stone	B + Lime–stone	C	C + Lime–stone	D	A	A + Lime–stone	B + Lime–stone
Cd	mg/l	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.005	<0.005	<0.005
CN^-	mg/l	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
P	mg/l	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.07	<0.05	<0.05
Pb	mg/l	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.005	<0.005	<0.005
Total–Cr	mg/l	<0.05	<0.05	0.07	<0.05	<0.05	<0.05	<0.05	<0.05	0.07
Cr^{6+}	mg/l	<0.04	<0.04	<0.04	<0.04	<0.04	<0.05	<0.04	<0.04	<0.04
As	mg/l	0.04	<0.05	<0.05	<0.01	<0.01	0.03	<0.05	<0.05	<0.05
Total–Hg	mg/l	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Alkyl–Hg	mg/l	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
PCB	mg/l	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005

4. Conclusions

Four types of sewage sludge cake, each having different properties, were subjected to combustion experiments using the pilot-scale CFB incinerator. As a result, the following conclusions were obtained regarding the applicability of the CFB furnace to sewage sludge incineration.

(1) The CFB furnace can be used to incinerate a wide variety of sewage sludge cakes by forming a fluidization mode optimized for damp material in the riser.

(2) It is possible to simultaneously reduce both NOx and N_2O by utilizing two-stage combustion and the high-temperature field in the upper zone of the riser. It is also possible to reduce the CO concentration, giving complete combustion.

(3) It is possible to reduce the SOx concentration by in-furnace desulfurization.

(4) No leaching of hazardous substances from fly ash or bed material was detected.

It was proven that the CFB technology developed for coal-fired boilers is satisfactory for sewage sludge incineration.

Therefore, CFB combustion can be applied to coal that has a high fixed carbon content and sewage sludge cake that has a high water content. The CFB technology may thus be applicable to combusting a variety of fuels and wastes as a means of effectively utilizing energy that will become increasingly diversified. For sewage sludge treatment in particular, the technology has the potential to achieve mixed combustion with screenings, grit, or other types of wastes, including energy recovery.

Based on the results obtained in these experiments, we are continuing to develop the CFB technology.

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