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Experimental Study of Improvement on Combustion Control of Fluidized Bed Combustion Chamber

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Abstract

Nippon Steel Corporation has carried out an experimental study using the Yawata waste incinerator plant in order to improve combustion control of a fluidized bed combustion chamber. For controlling the forming of dioxin, combustion control is very important in addition to conventional methods. In this paper, two studies about improvements on combustion control are reported. In the first study, combustion control by modifying gas flow at the freeboard are verified. The operational results of the experiments were studied using the numerical model of the combustion chamber. The modification of gas flow at freeboard was confirmed to be effective to obtain a compact design of fluidized bed combustion chamber for municipal waste. In the second, study, improved combustion control for sewage combustion with municipal waste was improved. In burning municipal waste and sewage, it is especially required to take combustion control into careful consideration. In this experiment, a new device for supplying sewage for the appropriate controlling combustion, and verified its effectiveness to combustion control and an effective reduction of dioxin was developed.

1. Introduction

Municipal solid waste (MSW) is burned in fluidized bed incinerators by many local governments in Japan. Co-incineration of sewage sludge with MSW is attracting attention as a method for not only completely burning MSW but also for making effective use of the heat that is generated. Generally, sewage sludge incinerators use oil or other auxiliary fuels as source of heat, whereas the co-incineration of sewage sludge and MSW has a recycle aspect in that the calorific value of the MSW itself is employed as source of heat.

For the incineration of MSW singly or in combination with sewage sludge, development of combustion technology to ensure complete combustion has been continued to date, in order to minimize the generation of air pollutants for environmental protection and to reduce the amount of ash to be land-filled as much as possible[1-3]. Enforcement of new dioxin guidelines made it all the more important to develop combustion technology to reduce the emissions of dioxin, a hazardous material. The most important consideration with respect to the incineration of waste in fluidized bed incinerators is that the combustion of waste in the bed should be kept at its optimum in response to unavoidable change in the properties of waste during combustion and it should be maintained under such conditions as to minimize the formation of hazardous materials in the free-

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This report presents the results of two studies conducted to improve the combustion performance of fluidized bed incinerators. The first study verified, in an actual incinerator, the validity of several measures for improving the combustion performance of the incinerator by controlling the gas flow in the freeboard, and it devised a method for improving gas flow and combustion that is adoptable on fluidized bed incinerators. The combustion improvement measured in the actual incinerator is reported here, together with the combustion improvement verified by a numerical analysis model. The second study developed an original sludge charging unit to perform complete combustion control, because the co-incineration of municipal solid waste with sludge or the like calls for due consideration of combustion control. The effectiveness of the sludge-charging unit in improving combustion control and reducing the emissions of dioxin as verified in the actual incinerator is also reported.

2. Fluidized Bed Incinerator at Yawata Works

Nippon Steel Corporation (NSC) has an environmental technology development center established in Kitakyushu City to develop technology for environmental engineering. The center has testing equipment for melting refuse and incineration residue, for incinerating industrial solid wastes, and for burning coal, refuse-derived fuel (RDF) and the like with high efficiency. A fluidized bed incinerator is installed at NSC's Yawata Works and used to conduct various types of tests.

The fluidized bed incinerator was originally installed to burn about 30 tons of industrial solid waste generated per day at the Yawata Works. It is regularly operated for the original purpose and is also used for incineration testing of various types of wastes, including sewage sludge, and for technology development. This private equipment is unique in that it was built to the same technical requirements as met by fluidized bed incinerators for local governments and was approved by Kitakyushu City as a municipal solid waste (MSW) combustion unit. The solid wastes generated at the Yawata Works have an average calorific value of 4,560 kcal/kg, about 1.5 times higher than that of the MSW burned by local governments. This presents a unique set of operating conditions for the fluidized bed incinerator at the Yawata Works. The equipment outline and flow chart of the Yawata fluidized bed incinerator are shown in **Table 1** and **Fig. 1**, respectively.

Table 1 Equipment outline of fluidized bed incinerator

1. Incinerator type	Fluidized bed
2. Refuse	Industrial solid waste
3. Refuse throughput	30 t/24h
4. Lower calorific value of refuse	4,560 kcal/kg-wet
5. Exhaust gas treatment	Scrubber + bag filter

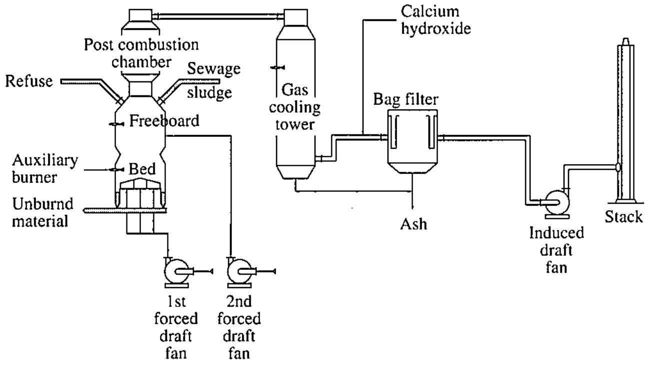


Fig. 1 Equipment flow sheet of fluidized bed incinerator

3. Improvement in Gas Flow and Combustion in Freeboard

3.1 Construction and combustion conditions of fluidized bed incinerator

Fig. 2 shows the vertical section of the fluidized bed incinerator at the Yawata Works and the CO concentration reduction when the MSW is burned in the Yawata incinerator. The incinerator consists of three main parts: fluidized bed, freeboard, and post-combustion chamber. The waste charged into the incinerator is subjected first to primary combustion and thermal decomposition in the fluidized bed. Most of the gas produced by thermal decomposition is burned in the freeboard. The post-combustion chamber completely burns the gas components left unburned in the freeboard, and keeps the gas at a temperature of 850°C or under for a sufficient length of time to prevent the formation of dioxin. The post-combustion chamber has the important functions of completely burning the gas and preventing the formation of dioxin. As can be seen from the distribution of unburned carbon monoxide (CO) in Fig. 2, most of the combustion process is almost completed in the freeboard, and the contribution of the post-combustion chamber to the entire combustion process is very low.

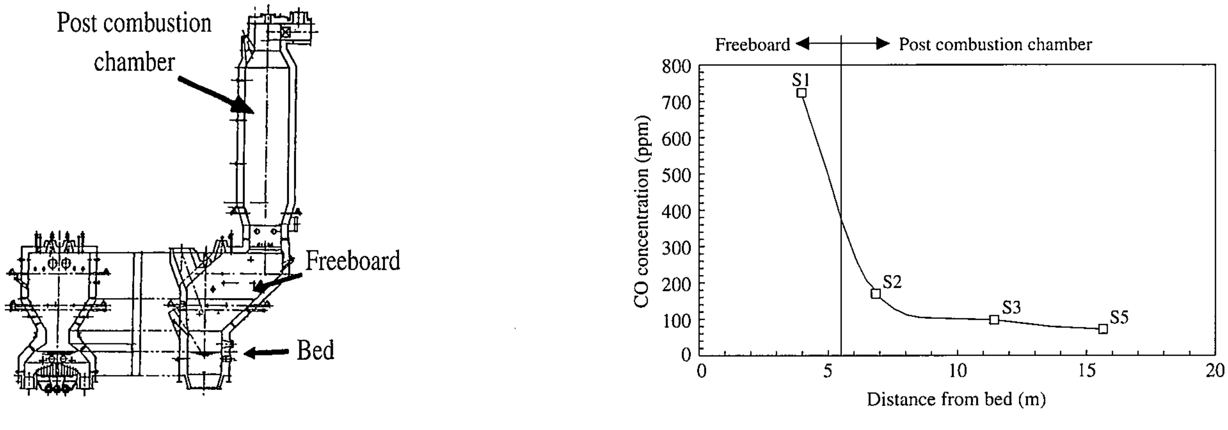


Fig. 2 Vertical section of incinerator and CO concentration distribution (before modification)

The post-combustion chamber accounts for about a half of the overall height of the incinerator. This is one constraint for the equipment size reduction of the incinerator. As noted above, the post-combustion chamber is provided to keep the gas from the freeboard at the desired temperature for such a long time as to achieve the complete combustion of the unburned gas component CO and to inhibit the generation [formation] of dioxin. The post-combustion chamber was designed as an extremely simple cylindrical structure to confirm the basic behavior of gas combustion and to enhance the reliability of the overall equipment.

Improvement in the mixing of unburned gas and combustion air is considered a basic method for promoting the gas combustion. This study was made to devise measures for intensifying this mixing in the post-combustion chamber of the cylindrical form and to verify the validity of the developed measures in the Yawata incinerator.

3.2 Measure for intensifying mixing in post-combustion chamber and experimental results

3.2.1 Measure for intensifying mixing

When studying how to intensify the mixing of the unburned gas and combustion air in the post-combustion chamber, it was noted that the concentration of unburned CO in the gas flow direction of the incinerator greatly diminished at the connection between the freeboard and the post-combustion chamber, as shown in Fig. 2. The reduction in the concentration of unburned CO at the connection may be explained as follows. The gas rising from the fluidized bed collides against the ceiling of the freeboard and is stirred there. The gas is stirred further by the restriction of the gas flow path at the connection.

To verify this reasoning, it was decided to equip the post-combustion chamber with baffle plates to provide impingement and restriction effects as shown in **Fig. 3** and to verify the behavior of unburned CO before and after the baffle plates.

3.2.2 Experimental results in Yawata incinerator

The municipal solid waste (MSW) generated in Kitakyushu City was used as experimental material. Main experimental conditions are given in **Table 2**, and gas-sampling positions are shown in **Fig. 4**. The experimentally measured CO concentrations are shown in **Fig. 5**. The following can be understood from the experimental results.

(1) Comparison of reduction in concentration of unburned CO

After the installation of the baffle plates, the reduction in the CO concentration across the baffle plates is conspicuous as shown in Fig. 5. As a result, the CO concentration at the outlet of the post-combustion chamber is lower than without the baffle plates. This is because the baffle plates not only reduced the average CO concentration during normal combustion, but also ensured stable mixing and agitation to prevent the CO concentration from peaking as the combustion conditions varied with the waste properties or with the waste feed rate over a short period.

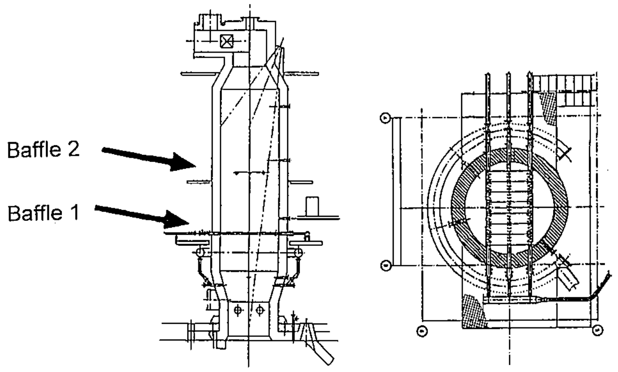


Fig. 3 Baffle plates installed in post-combustion chamber

Table 2 Main experimental conditions of first study

1. Refuse	Municipal solid waste
2. Refuse throughput	1,944 kg/h
3. Lower calorific value of refuse	2,240 kcal/kg-wet
4. Bed temperature	600 °C
5. Freeboard temperature	850 °C

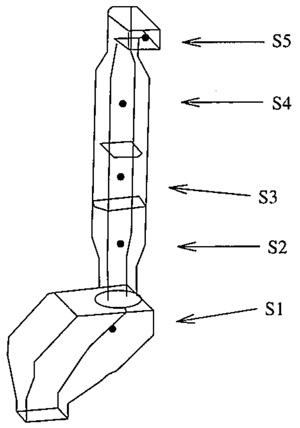


Fig. 4 Gas sampling positions

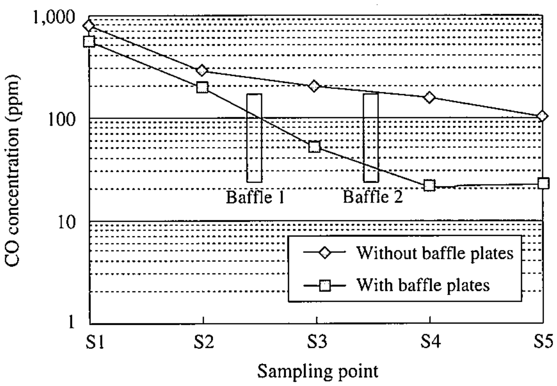


Fig. 5 CO concentration distributions

(2) Effects of baffle plates

The experimental baffle plates were installed to provide a cross-sectional area reduction of 50% in the baffle plate installation section and to double the exhaust gas flow velocity through the baffle installation section.

As evident from the experimental results, the baffle plates can fully improve the combustion of the gas in the post-combustion chamber due to the effects of doubling the gas flow velocity and improving the gas flow through repetition twice of impinging, branching, contracting and flowing together.

3.3 Verification with numerical analysis model

The experimentally-clarified effects of the baffle plates in improving the combustion of the gas were verified by numerical analysis.

3.3.1 Numerical analysis model

The numerical analysis was performed by a three-dimensional steady-state finite-element method with the general-purpose software Fluent (version 4). The following initial conditions were assumed:

(1) The combustible gas is a single-component gas whose molar weight corresponds to that of MSW.

(2) The combustible gas gushes out of the center of the fluidized bed in a rising stream twice as large as normal during simulated sudden combustion.

The excess air ratio and other conditions were made the same as the experimental conditions. The numerical analysis model used is illustrated in **Fig. 6**.

3.3.2 Comparison of numerical analysis results and experimental results

The numerical analysis-elucidated difference in the CO concentration distribution before and after the installation of the baffle plates is illustrated in **Fig. 7**. Like the experimental results, the CO concentration slowly decreased in the post-combustion chamber before the installation of the baffle plates, and the combustibility of the gas is lower in the post-combustion chamber than in the contraction at the inlet of the post-combustion chamber. After the installation of the baffle plates, the CO concentration of the gas suddenly dropped to 1 ppm before passage through the second baffle plate. The combustibility of the gas was found to be improved by the installation of the baffle plates. The numerical analysis also verified the improvement in the gas combustion with the installation of the baffle plates.

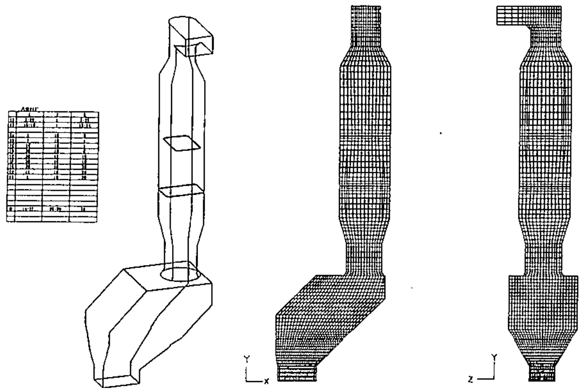
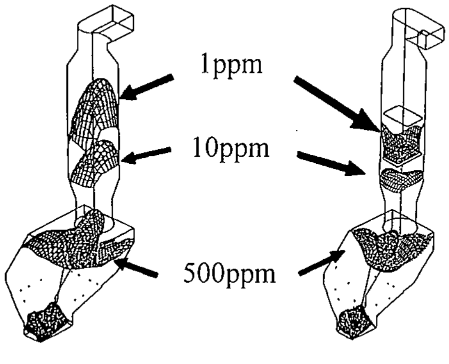


Fig. 6 Numerical analysis model



Before modification **After modification**

Fig. 7 Comparison of numerical analysis results before and after modificationg

Table 3 Comparison of experimental and numerical analysis results

Sampling point	Numerial analysis		Experiment	
	CO (ppm)	O_2 (%)	CO (ppm)	O_2 (%)
S1	596.5	10.56	539.0	8.37
S2	41.6	10.24	190.7	8.36
S3	1.8	10.25	50.0	8.92
S4	0.18	10.24	21.3	9.03
S5	0.06	10.24	7.0	8.06

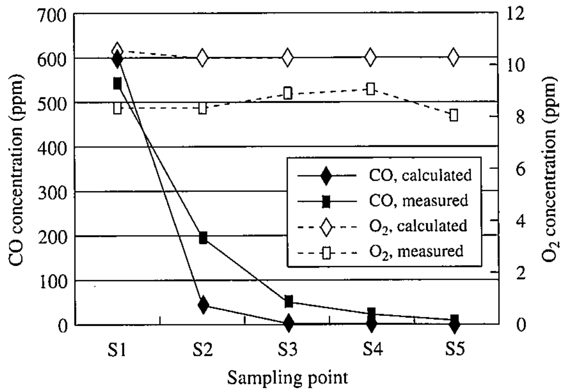


Fig. 8 Measured and calculated CO and O_2 concentration distributions

Next, the numerical analysis results and the experimental results after the installation of the baffle plates are compared and checked for agreement. **Table 3** and **Fig. 8** show the CO and O_2 concentration values and distributions as determined by the numerical analysis and experiment. Fig. 8 shows that the calculated CO concentration distribution is different from the measured CO concentration distribution in absolute values, but is in good agreement with the measured CO concentration distribution in terms of a sudden drop from the sampling points S1 to S2 and a further drop caused by the baffle plates before and after the sampling point S3. Similarly, the calculated O_2 concentration is different from the measured O_2 concentration in absolute values, but agrees well with the measured O_2 concentration in tendency. The calculated concentrations somewhat differ from the measured concentrations in absolute values, because the initial conditions and boundary conditions of the numerical analysis are not sufficient to represent the actual phenomena and because the experiment involves waste quality change and measurement errors. Given these results, improving the accuracy of numerical analysis conditions and reducing the errors of measurement are still required.

4. Improvement in combustibility of Sewage Sludge with Municipal Solid Waste

4.1 Sludge feed method and combustion conditions

4.1.1 Feed method into incinerator

The method of feeding sewage sludge into the Yawata incinerator is shown in **Fig. 9**. The sludge is charged into the hopper, withdrawn by the screw conveyor at the bottom of the hopper, sent to the uniaxial screw pump of the fixed displacement type, and piped into the incinerator. The sludge may be fed into the incinerator by a pump installed in a single pipe through the wall of the incinerator or by a machine that cuts, disintegrates, and dispersively charges the sludge

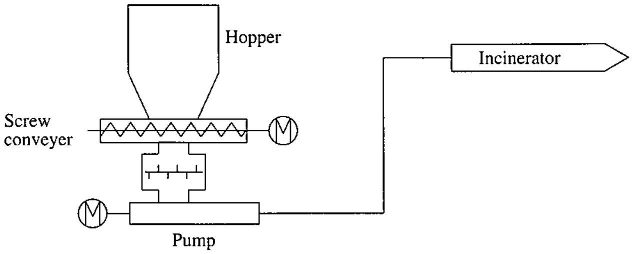


Fig. 9 Sludge feed flow sheet

into the incinerator. With the latter mechanical method, the sludge deposited on the cutting and disintegrating parts detracts from the sludge dispersion effect. At the same time, there is the possibility that cut pieces of the sludge may coalesce into large lumps. The former pumping method cannot be expected to provide the sludge dispersion effect, but is relatively free from sludge deposits and is high in maintainability.

4.1.2 Combustion conditions

Municipal solid waste (MSW) and sewage sludge (sludge co-incineration ratio of 23.8%) were used as the experimental materials. The sludge was pumped into the incinerator. Main experimental conditions are given in **Table 4**, and measured bed temperature changes are shown in **Fig. 10**. When MSW was burned alone, the bed temperature was maintained at a stable level of 650°C ± 2°C as shown in Fig. 10. When MSW and sludge were co-incinerated, the bed temperature suddenly dropped to 600°C or less immediately after the sludge was fed into the incinerator. Thermometers installed in several positions in the bed read different temperatures, and the sludge was intermittently added in large lumps of about 100 mm in size. From these conditions, it is presumed that the local increase in the sludge feed to the bed caused the local drop of the bed temperature and worsened the sludge flow in the bed.

Table 4 Main experimental conditions of second study

1. Refuse	Municipal solid waste	Sewage sludge
2. Lower calorific value of refuse	2,240 kcal/kg-wet	220 kcal/kg-wet
3. Water	40.6%-wet	83.7%-wet
4. Bed temperature	650 °C	
5. Freeboard temperature	850 °C	

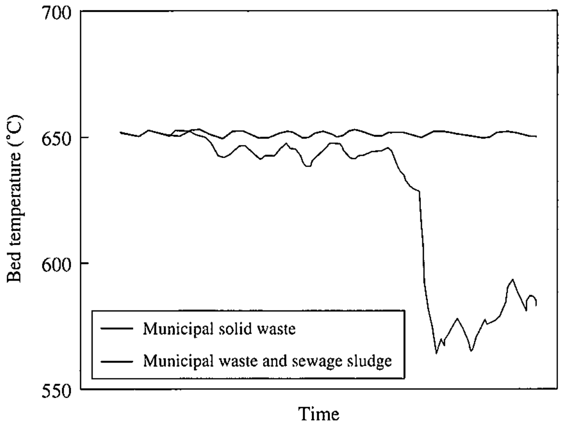


Fig. 10 Change in bed temperature

The bed temperature continued to drop from a few minutes to 15 to 30 minutes after the stop of the sludge feed and then rose. Blue flames, probably due to the gasification of the sludge, were observed from the bed over as long as 20 min. This may be taken to mean that the sludge lumps settle through the bed, accumulate there, and burn there for a long period of time.

4.2 Development of sludge charging unit and improvement in sludge flow

4.2.1 Development of sludge charging unit

When we developed a sludge-charging unit, we focused attention on the size reduction and dispersion of sludge lumps to solve the above-mentioned problems. This unit was designed to stabilize the combustion of sludge in the incinerator, improve the uniformity of the sludge treating throughput, and enable the stable treatment of the sludge at a high throughput.

With the above-mentioned considerations taken into account, the sludge charging unit shown in **Fig. 11** was developed. The unit blows air through the inside and outside of the sludge outlet to shear sludge lumps. This shearing of the sludge lumps is expected to provide the size reduction and dispersion of the sludge.

4.2.2 Improvement in sludge flow

An off-line sludge feed test was conducted to verify the perfor-

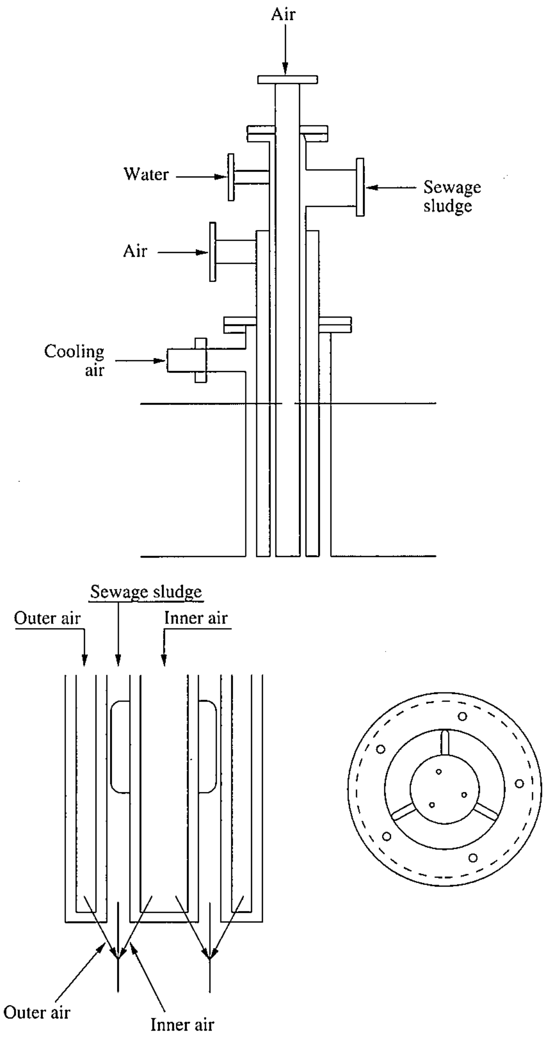


Fig. 11 Sectional views of sludge charging unit

mance of the sludge-charging unit that was devised. The variation of the size of sludge lumps with the inner and outer air flow rates is shown in **Fig. 12**. The relationship between the total air flow rate and the sludge dispersion is shown in **Fig. 13**. The dispersion characteristics refer to the proportions of sludge lumps falling over the total bed area and quarter bed area of the Yawata incinerator. As shown in Fig. 12, the sludge lumps can be changed to various sizes by changing the inner and outer air flow rates. It is also known that the sludge lumps are sheared according to the supply balance of the inner or outer air. It is evident from Fig. 13 that the sludge lump falling range can be expanded by increasing the total air flow rate.

The above discussion suggests that the flow of the sludge in the incinerator can be improved by selecting sludge lumps of such a size as to cause no sudden combustion in the freeboard and as not to impede the flow of the sludge lumps in the bed and by determining such air flow rates and inner/outer air balance as to maintain the dispersion of sludge so that the sludge does not adhere to the incinerator wall.

4.3 Combustion test results in Yawata incinerator and adoption at new incineration plant in Noboribetsu City

The above-mentioned on-line test confirmed that the size of sludge lumps can be freely set. Prior to a combustion test, a preliminary experiment was conducted to determine the optimum size of sludge lumps as required to maintain appropriate levels of incinerator top temperature and bed temperature and to co-incinerate municipal solid waste (MSW) and sewage sludge. **Fig. 14** shows the ratio of the CO concentration when the MSW alone was burned to the CO concentration when MSW and sewage sludge were burned together at different ratios. Auxiliary burners were not used in both cases. When the sludge was burned together with the municipal solid waste to a co-incineration ratio of about 32%, the CO concentration was maintained at a level comparable to the CO concentration when MSW alone was burned. The co-incineration ratio of 32% was set as the upper limit above which auxiliary combustion is required to maintain heat balance in the incinerator. It was also confirmed that the generation of dioxin was the same as that recorded when MSW alone was burned. These results suggest that the fluidized bed incinerator under construction at a new incineration plant in Noboribetsu City will be able to achieve good sludge flow in the fluidized bed and stable combustion at a maximum co-incineration ratio of 18.3%.

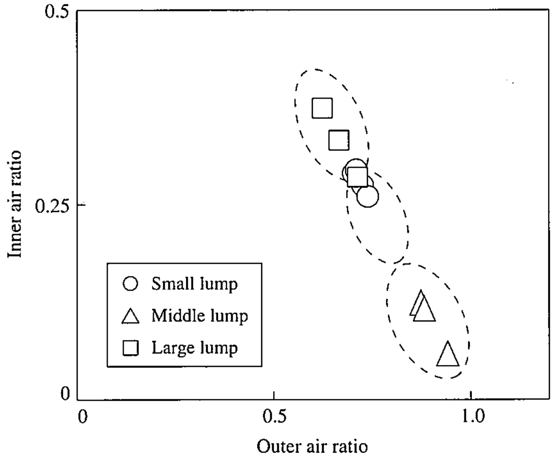


Fig. 12 Relationship between air flow rates and sludge lump size

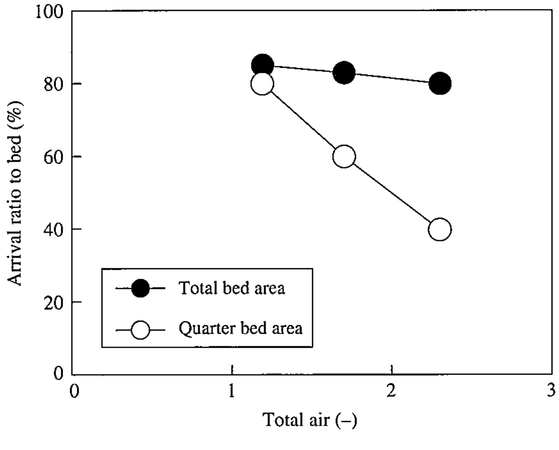


Fig. 13 Relationship between total air flow rate and sludge falling range

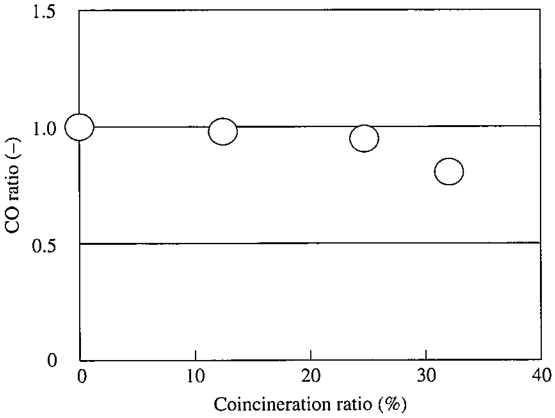


Fig. 14 Relationship between CO concentration ratio and sludge co-incineration ratio

5. Conclusions

This report has presented the results of two studies conducted to improve the combustion performance of a fluidized bed incinerator.

As a measure for improving combustion in the freeboard by controlling gas flow there, the first study devised the method of installing baffle plates with gas impingement and restriction effects in the post-combustion chamber whose contribution to overall combustion in the incinerator is low. The behavior of unburned carbon monoxide (CO) across each baffle plate was verified by experimentation in a fluidized-bed incinerator at Nippon Steel's Yawata Works and by numerical analysis.

The results of the first study may be summarized as follows:

(1) The results of experimentation in the Yawata incinerator show that the concentration of unburned CO is sharply reduced across each baffle plate and that combustion in the post-combustion chamber can be improved by the installation of the baffle plates.

(2) The numerical analysis also confirmed the effectiveness of the baffle plates in improving combustion in the post-combustion chamber. The experimental results in the Yawata incinerator agree well with the numerical analysis results.

The reduction in the CO concentration in the combustion experiment pointed to the possibility of reducing the incinerator volume by about 30% as compared with conventional fluidized bed incinerators without such baffle plates.

As a measure for improving the bed temperature and bed material flow conditions when municipal solid waste (MSW) and sewage sludge are co-incinerated, the second study devised a sludge-charging unit that can set the size of sludge lumps at any desired level by changing the inner and outer air flow rates through the sludge inlet of the incinerator. In the combustion test conducted with the sludge charging unit in the Yawata incinerator, it was confirmed that when a high percentage of sludge was co-incinerated with the municipal solid waste, the resultant CO concentration and dioxin formation were equivalent to those observed when municipal solid waste alone was burned.

The results of the second study may be summarized as follows:

(1) To achieve complete combustion control, such a sludge-charging unit was devised that can change the size of sludge lumps to any desired level.

(2) In the combustion test conduced with the sludge-charging unit in the Yawata incinerator, the sewage sludge was successfully co-combusted with the municipal solid waste without using auxiliary burners and under conditions equivalent to those observed when the municipal solid waste alone was burned.

A new MSW incineration plant is under construction for Noboribetsu City (scheduled for completion in March 2000). Based on the new dioxin guidelines enforced from 1998, the new plant is designed for stable co-incineration of a high proportion of sewage sludge with MSW from the standpoint of a thermal cycle for utilization of the heat of incineration of MSW.

Table 5 gives the equipment outline of the Noboribetsu incineration plant. In addition to these fluidized bed incinerator combustion performance improving techniques, Nippon Steel has a system to meet Japan's new toughed dioxin guidelines with its own techniques for feeding waste at a constant rate with a waste feeder, for feeding activated carbon before a bag filter, and for catalytically cracking incinerator exhaust gases, among other techniques. Development of clean fluidized bed incinerator equipment with smaller dioxin emissions yet reducing overall equipment size are future goals.

Table 5 Equipment outline of new incineration plant

1. Incinerator type	Fluidized bed
2. Refuse	Municipal solid waste and sewage sludge
3. Refuse throughput	2.56 t/h
4. Lower calorific value of refuse (standard)	2,000 kcal/kg-wet
5. Exhaust gas tretment	Scrubber + bag filter
6. Mixture rate of sewage	18.3%

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