

# Pressurized Fluidized Bed Combustion of Sewage Sludge\* (Energy Recovering from Sewage Sludge by Power Generation System)

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A conceptual design of an energy recovering system from sewage sludge was proposed. This system consists of a pressurized fluidized bed combustor, a gas turbine, and a heat exchanger for preheating of combustion air. Thermal efficiency was estimated roughly as 10–25%. In order to know the combustion characteristics of the sewage sludge under the elevated pressure condition, combustion tests of the dry and wet sewage sludge were carried out by using laboratory scale pressurized fluidized bed combustors. Combustibility of the sewage sludge was good enough and almost complete combustion was achieved in the combustion of the actual wet sludge. CO emission and NO<sub>x</sub> emission were marvelously low especially during the combustion of wet sewage sludge regardless of high volatile and nitrogen content of the sewage sludge. However, nitrous oxide (N<sub>2</sub>O) emission was very high. Hence, almost all nitrogen oxides were emitted as the form of N<sub>2</sub>O. From these combustion tests, we judged combustion of the sewage sludge with the pressurized fluidized bed combustor is suitable, and the conceptual design of the power generation system is available.

**Key Words:** Pressurized Fluidized Bed Combustion, Sewage Sludge, Power Generation, Combustion Characteristics

## 1. Introduction

Pressurized fluidized bed combustion (PFBC) technology has recently entered the commercial stage. Usually, pressurized fluidized bed boiler, gas turbine and steam turbine consist a combined cycle power generation system<sup>(1)</sup>. High temperature and pressure flue gas, generated in the pressurized fluidized bed boiler, is introduced directly into a gas turbine after passing through a hot dust removal system such as a ceramic filter module or a cyclone separator. In Japan, three PFBC based combined cycle power generation units (85 MWe, Tomatoh-Atsuma; 250 MWe, Osaki; 360 MWe, Karira) are under commercial operation. PFBC allows the combustion of low grade solid fuels with high combustion efficiency due to high

combustion rate and gives low environmental impacts due to low emission<sup>(2)</sup>. From the technical point of view, PFBC technology is one of the best combustion technologies for solid fuels. However, net thermal efficiency is below 41–42%, because inlet temperature of gas turbine is limited below 1 123 K. Usually, operation higher than 1 200 K is impossible due to ash melting trouble and decreasing of in-situ desulfurization efficiency. On the other hand, thermal efficiency of conventional pulverized coal combustion power generation system is improved rapidly by increasing of steam pressure and temperature conditions. Thermal efficiency of the recent system is almost same as that of PFBC. Advantages of PFBC against the conventional system seem to be small. Hence, construction of PFBC is held or cancelled not only in Japan but also in other countries. A new application of PFBC is required.

Utilization of wastes as an energy source is needed to lower the consumption of fossil fuel. Annual production of sewage sludge is 5 million tons, and almost sewage is incinerated in Japan. However, energy recovering from the sewage sludge is not yet done because of a high water content of the sewage sludge (80 wt%). In many sewage sludge incinerators, co-firing fuels are used to maintain a suitable combustion temperature. However, water content

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of sewage sludge will be lowered less than 75 wt% by the improvement of dewatering technology. Because an excess heat exists when water content of the sewage sludge is lowered, a new energy recovering system from the sewage sludge is required. Hence, we proposed a new energy recovering system for the sewage sludge by introducing PFBC technology. However, very few data on combustion of the sewage sludge by PFBC were published because PFBC was mainly applied for coal combustion. In this paper, results of combustion tests of the sewage sludge by using laboratory scale PFBCs are presented.

## 2. Energy Recovering System

A new energy recovering system for the sewage sludge is illustrated in Fig. 1. Main components are a pressurized fluidized bed combustor, a hot gas cleaning system, a gas turbine, a compressor, a power generator, and a heat exchanger. Power is generated only by the gas turbine. Remaining heat contained in the gas is used the preheating of the combustion air. The estimated thermal efficiency, which depends on the operating pressure and temperature, is 15–25%. The capacity of this system may be 100–200 t/day, which fits to the typical capacity of current sewage sludge incinerators in Japan. If necessary, co-firing fuel such as coal, biomass, and other fossil fuels can be used to improve the thermal efficiency.

Sewage treatment plants consume large electricity. If electricity can be generated by the sludge incineration, a large reduction in electricity consumption can be achieved. From the technological point of view, the construction of this system seems to be easy, because almost component technologies have been developed during the development of the coal-fired PFBC. However, combustion characteristics of the sewage sludge in elevated pressure condition are not clearly understood. Hence, combustion tests of the actual sewage sludge are needed to develop the system.

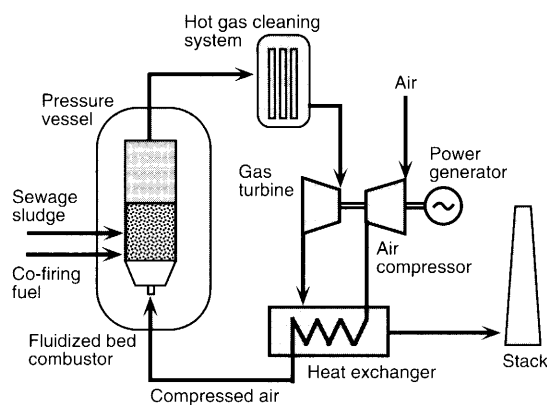


Fig. 1 Power generation system by PFBC

## 3. Experimental Apparatus

### 3.1 Laboratory scale PFBC system and combustors

A pressure vessel with 1 200 mm inside diameter and 3 200 mm height, and laboratory scale PFBC systems are illustrated in Figs. 2 and 3 respectively. The pressure vessel, made of stainless steel, consists of three parts and its design maximum pressure is 2.0 MPa. Eight view ports are attached to the wall of the pressure vessel to allow visual observations of the fluidized bed combustor inside the pressure vessel. This PFBC system is operated with the maximum operating pressure of 1 MPa and the highest bed temperature of 1 223 K. Maximum heat input at 1 MPa is 7 kW<sup>(3)</sup>.

Two fluidized bed combustors, which are shown in Fig. 4, are designed and constructed. Dry sewage sludge was burnt by the first combustor to observe combustion behaviors, and wet actual sewage sludge was burnt by the second to know the total combustion characteristics. A main component of the first fluidized bed combustor is made of a transparent quartz tube and a gold image furnace to allow the visual observation of the fluidized bed. A gold plating on the inside surface of the furnace's trans-

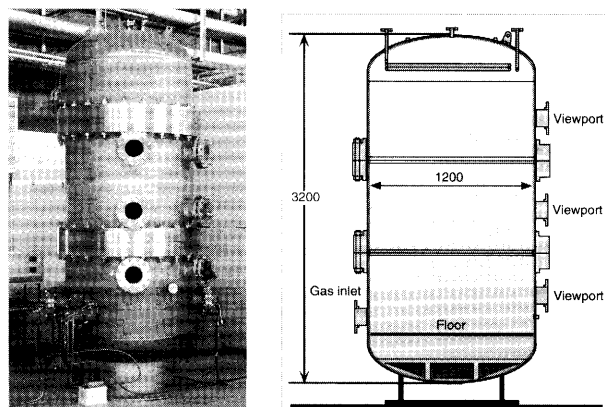


Fig. 2 Photograph and sketch of pressure vessel

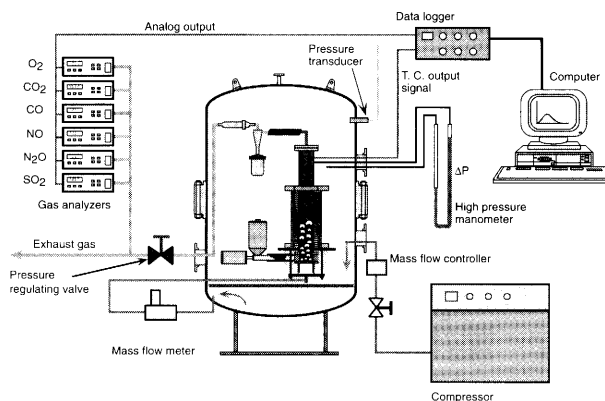


Fig. 3 Pressure vessel and lab-scale PFBC system

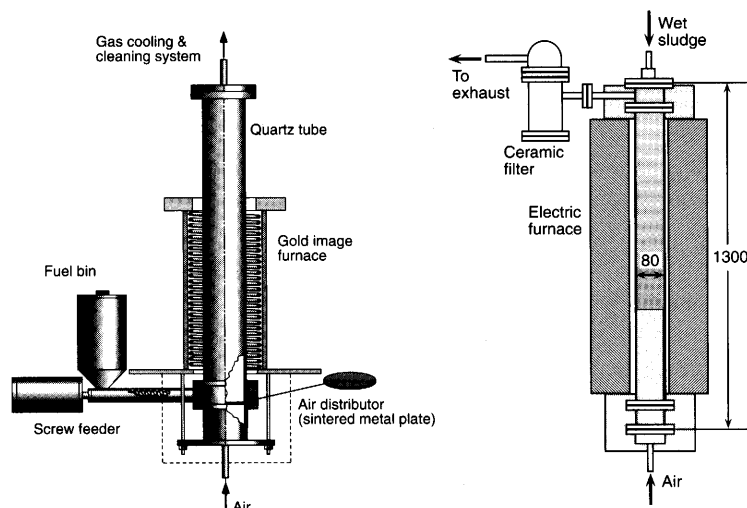


Fig. 4 Detail of fluidized bed combustors  
 Left: Fluidized bed combustor for dry sewage sludge  
 Right: Fluidized bed combustor for wet sewage sludge

parent quartz tube passes visible light at high temperature condition. Hence combustion behaviors can be observed directly. Inside diameter and height of the fluidized bed combustor are 80 mm and 1 000 mm respectively. The dried sewage sludge, crushed to 0.25 – 1 mm size, is fed to the bottom of the bed by a screw feeder directly attached to the fluidized bed as illustrated in Fig. 4. Fly ash is separated from the flue gas by a glass cyclone and a ceramic filter element, which is used in dust sampling.

The second combustor was made of stainless steel, and the capacity of the electric furnace was larger than that of the first to allow the combustion of wet sludge. Inside diameter and height are 80 mm and 1 300 mm respectively. Actual sewage sludge was fed continuously to an injection nozzle located at the top of the combustor by a high-pressure pump. A ceramic filter module, which is commonly used in the full scale PFBCs, was used as a dust collector.

Compressed air was supplied from a compressor to the pressure vessel through a mass flow controller. Flow rate of the air entering to the combustor was measured by a mass flow meter. A pressure regulating valve located at the exit of the pressure vessel controlled inside pressure of the vessel. Bed material used in both combustors was quartz sand with a mean diameter of 0.25 mm and static bed height is 300 mm. Bed temperatures were measured by type-K thermocouples in the bed. The diameter of bed material is smaller than that in full scale PFBC and the ratio of bed diameter to bed height was small in the both lab-scale PFBCs. This means that the fluidization mode will be essentially slugging. It leads higher vertical mixing than in a full scale PFBC. The superficial air velocity was kept constant at 15 cm/sec for both fluidized bed combustors in all operating pressures in order to keep the

fluidization condition. From this experimental condition, combustion of the dry sludge was limited at the operating pressure less than 0.4 MPa due to the limitation of the maximum feed rate of dry sludge. On the contrary, combustion of the wet sludge was limited at the operating pressure higher than 0.6 MPa due to the minimum feed rate of wet sludge by the pump.

Measurements of gas components in flue gas were made with continuous gas analyzers.  $\text{CO}_2$ , CO, and  $\text{N}_2$  were measured by infrared analyzers.  $\text{NO}_x$  and oxygen were measured by a chemiluminescence analyzer and a paramagnetic analyzer respectively. A gas chromatograph was employed to measure  $\text{N}_2\text{O}$  and CO. Gas sample was introduced to the gas chromatograph with 5 minutes interval. In the case of the wet sludge combustion, water vapor was condensed and separated from the sample flue gas by cooling before introduction to the gas analyzing system because volumetric water vapor concentration exceeded 40%. No  $\text{SO}_2$  absorbent, such as limestone, was added to the bed in the experiments.

### 3.2 Sewage sludge

Analytical data of the dry and wet sewage sludge used are listed in Table 1. The wet sewage sludge was taken at an actual sewage treatment plant, and a small amount of water was added to lower the viscosity. Actual water content of wet sludge used was about 83 wt%. The second fluidized bed combustor can burn the wet sludge due to large heat input capacity of electric furnace even though high water content.

## 4. Experimental Results and Discussion

### 4.1 Visual observation

In the case of the dry sludge combustion, it was clearly showed by video observations that volatiles burned

Table 1 Analytical values of dry and wet sewage sludge

	Dry sludge	Wet sludge
Proximate analysis		
Moisture (wt%)	10.2	79.0
Volatiles (dry wt%)	62.2	71.3
Fixed carbon (dry wt%)	8.2	
Ash (dry wt%)	29.7	28.7
Ultimate analysis (dry wt%)		
C	38.3	29.8
H	4.8	4.0
N	4.7	5.0
S (combustible)	1.2	1.1
O	21.4	21.40
Higher heating value (MJ/kg-dry sludge)	17.1	-

mainly in the fluidized bed and very small part of volatiles escaped to the freeboard because combustion rate of volatiles becomes high in elevated pressure condition. There must be many flames at the surface of fluidized bed in an atmospheric laboratory scale FBC even though dry sludge particles were fed to the bottom of the bed, because bed height was not enough to achieve complete combustion of volatiles.

#### 4.2 Fundamental operability

Figure 5 shows a typical record of temperature change at 0.8 MPa in the case of wet sludge combustion. More than 4 hours continuous operation was achieved. In wet sludge combustion, bed temperature decreased after starting the feeding due to high water content. On the contrary, freeboard temperature increased. This behavior means that volatiles mainly burned at the freeboard section. Drying and devolatilization may occur in the bed. As mentioned above, volatiles could be burn-upped within the bed when dry sludge was fed into the bottom of the bed, because drying process was omitted. For actual incinerators, feeding of wet sludge to the surface of the bed is usual way. Hence, behaviors shown in Fig. 5 may be regular situation. The temperature difference in the bed was less than 35 K in the wet sludge combustion. The upper region of the bed was higher than the bottom region. This may be caused by drying and thermal decomposition of wet sludge in the bottom region.

Lowest bed temperature of bottom region to maintain the stable combustion was near 950 K. When bed temperature was lowered less than 950 K, CO emission was increased. This means stable combustion cannot be maintained. For actual full scale combustors, this bed temperature can be kept because combustion air is preheated and heat loss becomes low.

#### 4.3 Combustion efficiency and ash behavior

As char combustion rate becomes very large<sup>(4)</sup> and volatile content of sewage sludge is very high, combustion efficiency is supposed to be high. This expectation was confirmed experimentally. Carbon content in fly ash was less than 0.1 wt% and CO emission (shown later) was also

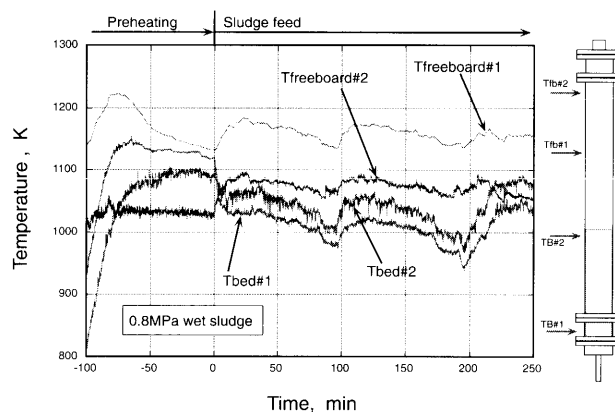


Fig. 5 Typical temperature change during the wet sludge combustion test

Fig. 6 Photograph of ash (wet sludge, 0.8 MPa)  
Left: Ash particle in the bed Right: Fly ash

very low in both dry and wet sludge combustion. This led higher than 99.9% of combustion efficiency.

Ash behavior is very important to design a dust collector. Figure 6 shows a photograph of in-bed ash and fly ash obtained in the wet sludge combustion. In the case of wet sludge combustion, more than 70 wt% of total ash was fly ash having mean diameter of 150  $\mu\text{m}$ . Remaining 30 wt% was in-bed ash having mm order diameter. This ash distribution was almost same as that of actual atmospheric fluidized bed sewage sludge incinerators. On the other hand, 80 wt% of total ash was in-bed ash in the case of dry sludge combustion. Moreover, the size of in-bed ash was the same size of original fed particle. This means that dry sludge produced hard ash.

This large difference in ash distribution in the both combustors should be made by existence of drying process. During the drying process, large wet particles may be broken in the bed and fine dry sludge particles were produced. Hence, the amount of the fine fly ash was increased in the wet sludge combustion. On the other hand, sludge particles burned with keeping its original size in the dry sludge.

From the results of wet sludge combustion tests, it was confirmed that the ash was produced mainly as the fly ash in the elevated pressure condition when wet sludge

was fed into the surface of the fluidized bed. As amount of fly ash is large, a high performance dust collector is required to protect the blade of gas turbine from the erosion.

Local high temperature spots are easily formed due to high combustion rate in PFBC condition. Especially, local temperature of burning char particles may be higher than mean fluidized bed temperature and agglomerates are formed when the melting point of the ash is low. When large agglomerates are formed in the bed, smooth fluidization can not be achieved and stable operation can not be continued. Troubles caused by ash melting is concerned for the sewage sludge combustion because melting point of the ash of the sewage sludge is low due to high alkali metal contents. However, no troubles due to ash melting were occurred in both dry and actual wet sewage sludge combustion. Main reason may be low fixed carbon content of sewage sludge and drying process.

#### 4.4 Emissions

**4.4.1 CO emission** As mentioned above, CO emission became so low that combustion efficiency became very high at elevated pressure condition. Figure 7 shows the CO emission as a function of O<sub>2</sub> concentration in the flue gas in the case of wet sludge combustion. At low O<sub>2</sub> concentration less than 4%, high CO emission was observed. However, CO emission decreased rapidly with increasing of O<sub>2</sub> concentration. In these experiments, CO emission was decreased with increasing of operating pressure as shown in Fig. 7. Though, this dependency of CO emission on O<sub>2</sub> concentration is commonly obtained in FBC, the dependency became very sharp one in the elevated pressure condition. In this case, 3.5% of O<sub>2</sub> concentration was a threshold value. Above experimental results agreed with a theoretical prediction. An empirical CO combustion rate expression<sup>(5)</sup> shows that CO combustion rate becomes very large in the elevated pressure condition or with high concentration of steam because of increasing of partial pressure of O<sub>2</sub> or H<sub>2</sub>O. More than 3 order

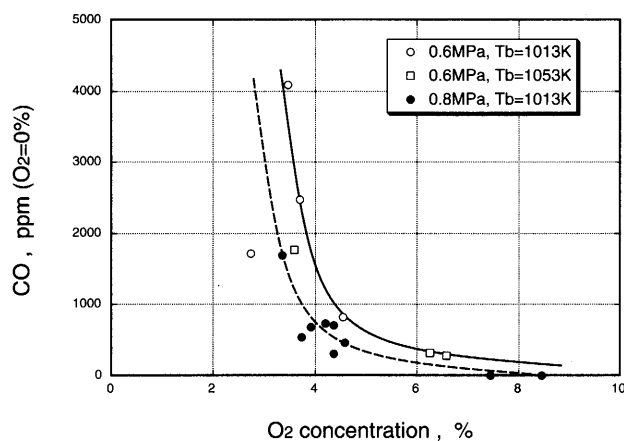


Fig. 7 CO emission as a function of O<sub>2</sub> concentration in the flue gas in the case of wet sludge combustion

of magnitude higher combustion rate than that in atmospheric condition may be achieved in the combustion tests of the wet sludge. A lower CO emission can be achieved when longer gas resident time is given. Freeboard length may become several meters in full scale combustor and mean residence time is estimated as few seconds. In these conditions, very low CO emission can be achieved.

**4.4.2 NO<sub>x</sub> emission** It is well known that NO<sub>x</sub> emission is reduced in the elevated pressure conditions<sup>(6)-(8)</sup>. Char particle reduces NO to N<sub>2</sub>. In PFBC condition, char concentration in the bed becomes high and bed height is usually designed as large. Hence, NO<sub>x</sub> emission of PFBC becomes low. Figures 8 and 9 show NO<sub>x</sub> emission in different O<sub>2</sub> concentrations and bed temperatures respectively in the wet sludge combustion. In Fig. 8, NO<sub>x</sub> emission was decreased slightly with the increasing of operating pressure, and decreased with the increasing of O<sub>2</sub> concentration. And NO<sub>x</sub> emission was not sensitive to the bed temperatures, which express the temperature of the bottom region of the bed, as shown in Fig. 9.

NO<sub>x</sub> emission in the dry sludge combustion at

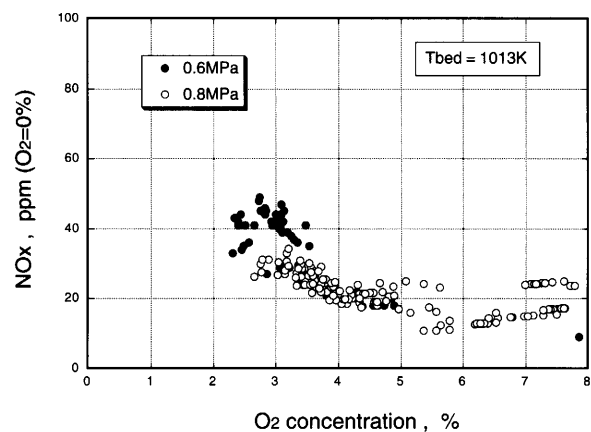


Fig. 8 NO<sub>x</sub> emission as a function of O<sub>2</sub> concentration in the case of wet sludge combustion

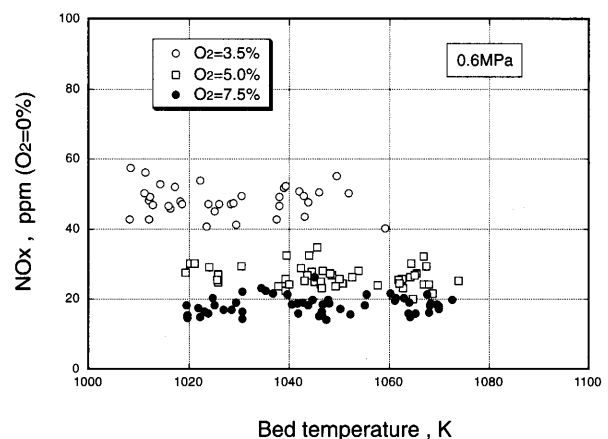


Fig. 9 NO<sub>x</sub> emission as a function of bed temperature in the case of wet sludge combustion

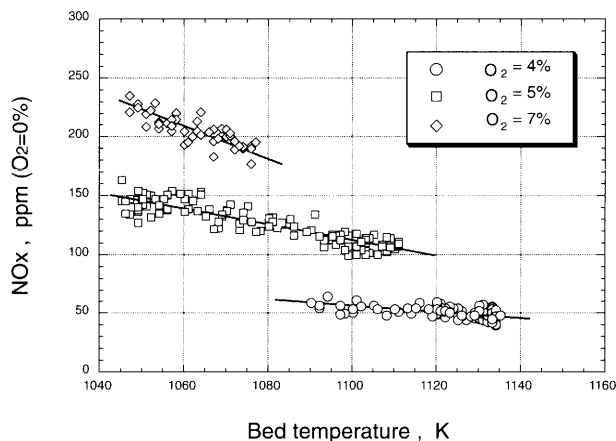
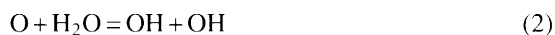


Fig. 10  $\text{NO}_x$  emission as a function of bed temperature in the case of dry sludge combustion (0.4 MPa)

0.4 MPa is shown in Fig. 10 to compare with the wet sludge combustion. In the wet sludge combustion,  $\text{NO}_x$  emission was decreased marvelously as shown in Fig. 9. This manner was also observed in actual sewage sludge incinerators operated at the atmospheric condition. Usually, less than 50 ppm of  $\text{NO}_x$  is emitted by sewage sludge incinerators. Effects of the steam concentration on  $\text{NO}_x$  formation were considered by kinetic calculations<sup>(9)</sup>. High concentration of steam can control the formation of  $\text{NO}_x$  from the nitrogen compounds by decrease of the concentration of O radicals in gas phase reactions as follow;



In reaction (2), O radical is captured by  $\text{H}_2\text{O}$ , hence formation of NO in reaction (1) is reduced.

As mentioned above, the dependency of  $\text{NO}_x$  emission on operating pressure and bed temperature in the wet sludge combustion was almost same as in the dry sludge combustion. However, effect of  $\text{O}_2$  concentration in the flue gas on  $\text{NO}_x$  emission was different from that in the dry sludge combustion. In the case of dry sludge combustion,  $\text{NO}_x$  emission increases with  $\text{O}_2$  concentration in the flue gas. This manner is common one<sup>(10)</sup>. On the contrary, dependency of  $\text{NO}_x$  emission on  $\text{O}_2$  concentration in the wet sludge combustion was opposite in the  $\text{O}_2$  concentration range less than 8%. To know the reason, more experimental and theoretical works are needed.

**4.4.3 Nitrous oxide ( $\text{N}_2\text{O}$ ) emission** It is well known that high amount of  $\text{N}_2\text{O}$ , which is one of the greenhouse gases, is emitted from the sewage sludge incineration. Figure 11 shows  $\text{N}_2\text{O}$  emission in the wet sludge combustion. In elevated pressure condition, high amount of  $\text{N}_2\text{O}$  was also emitted. Though more data are needed to final judgement, increasing of operating pressure leads higher  $\text{N}_2\text{O}$  emission. It is well known that there is a “trade-off” relationship between  $\text{NO}_x$  and  $\text{N}_2\text{O}$

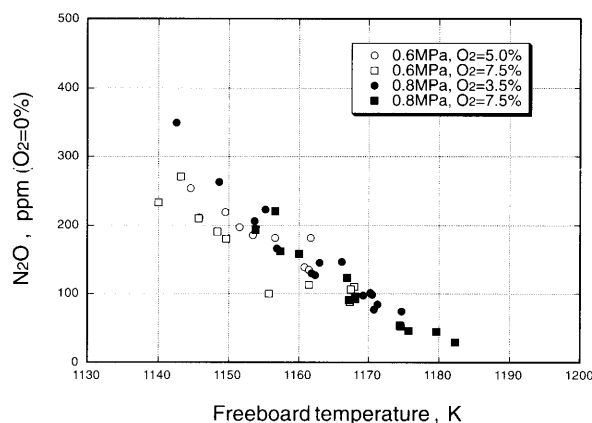


Fig. 11  $\text{N}_2\text{O}$  emission as a function of freeboard temperature (wet sludge)

emissions at different operating conditions such as bed temperature,  $\text{O}_2$  concentration in the flue gas, and rank of coal<sup>(10)</sup>. In different operating pressures,  $\text{NO}_x$  and  $\text{N}_2\text{O}$  emissions may also change each other in the trade-off relationship. Typical  $\text{N}_2\text{O}$  emission was higher than 200 ppm. This means 80% of nitrogen oxide was emitted in the form of  $\text{N}_2\text{O}$ , because typical  $\text{NO}_x$  emission was less than 50 ppm.  $\text{N}_2\text{O}$  emission was sensitive to the freeboard temperature, and rapidly decreased with increasing in the freeboard temperature. There may be no serious problem in the emissions except  $\text{N}_2\text{O}$ . An operation with higher bed temperature can decrease  $\text{N}_2\text{O}$  emissions without the increasing of  $\text{NO}_x$  emission.

## 5. Conclusion

In order to know the combustion characteristics of the sewage sludge under the elevated pressure condition, combustion tests of the dry and wet sewage sludge were carried out and following results were obtained.

(1) Combustibility was good enough and almost complete combustion was achieved even though with actual wet sludge.

(2) In the case of the wet sludge combustion, more than 70 wt% of total ash was fly ash and the remaining 30 wt% was in-bed ash. No ash melting troubles were occurred.

(3) CO emission and  $\text{NO}_x$  emission were marvelously low especially during the combustion of wet sewage.

(4) Nitrous oxide ( $\text{N}_2\text{O}$ ) emission was very high. This means almost all nitrogen oxides were emitted as the form of  $\text{N}_2\text{O}$ . To reduce  $\text{N}_2\text{O}$  emission, operation of higher bed temperature was very effective.

From the combustion tests, we judged the combustion of the sewage sludge by a pressurized fluidized bed combustor is suitable, and the conceptual design of the power generation system is available.

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