Fuel Processing Technology 90 (2009) 778–783

Contents lists available at ScienceDirect

Fuel Processing Technology

journal homepage: www.elsevier.com/locate/fuproc

Combustion characteristics of sewage sludge in an incineration plant for energy recovery

Takahiro Murakami [a,*], Yoshizo Suzuki [a], Hidekazu Nagasawa [b], Takafumi Yamamoto [b], Takami Koseki [c], Hitoshi Hirose [c], Seiichiro Okamoto [d]

[a] National Institute of Advanced Industrial Science and Technology (AIST), 16-1, Onogawa, Tsukuba, Ibaraki 305-8569, Japan
[b] Tsukishima Kikai Co., Ltd., 17-15, Tsukuda, 2-Chome, Chuo-ku, Tokyo 104-0051, Japan
[c] Sanki Engineering Co., Ltd., 1742-7, Shimotsuruma, Yamato, Kanagawa 242-0001, Japan
[d] Public Works Research Institute (PWRI), 1-6, Minamihara, Tsukuba, Ibaraki 305-8516, Japan

ARTICLE INFO

Article history:
Received 26 September 2008
Received in revised form 27 February 2009
Accepted 13 March 2009

Keywords:
Sewage sludge
Incineration plant
Energy recovery
Combustion characteristics
Pressurized fluidized bed

ABSTRACT

A new type of sewage sludge incinerator that combines a pressurized fluidized bed combustor and a turbocharger driven by flue gas was proposed. In this study, the operation and combustion characteristics of a demonstration plant were clarified, and the design data for a commercial plant were obtained. The steady operation exceeded 600 h in total. CO, NO_x, and N_2O emissions in the flue gas were less than half those of a conventional plant. At an incineration capacity of 100 t/day, an energy savings of approximately 50% can be achieved compared with a conventional plant because the forced draft fan (FDF), the induced draft fan (IDF) and the feed water pump are unnecessary. Also, pressurization allowed reduction of the combustor volume, so about 25% of supplementary fuel can be reduced. Consequently, CO_2 emissions originating from electric power consumption and supplementary fuel is expected to be reduced by about 40% annually compared with emissions from a conventional plant; in addition, the cost of fuel and electricity can be reduced by 23 million yen. Therefore, this advanced incinerator for sewage sludge can realize energy recovery and savings as well as a low environmental impact.

1. Introduction

Annual production of sewage sludge in Japan increased to 2.17 million t (d.b.) in 2004. About 70% of sewage sludge is incinerated [1–3]. In a typical conventional incineration plant (Fig. 1), de-watered sludge containing 80 wt.% moisture is supplied to a bubbling fluidized bed combustor fueled by a supplementary fuel such as natural gas or crude oil. Drying, devolatilization, and combustion take place in the combustor. Flue gas is exhausted from a stack into the atmosphere after first passing through an air preheater, a smoke-prevention preheater, a gas cooler, a bag filter, and a scrubber. Sludge incineration consumes electric power because the process utilizes many auxiliaries (Fig. 1). A typical incinerator with a capacity of 100 t/day, which is the average capacity in Japan, consumes 350 kW during steady operation [1,4]. In particular, the forced draft fan (FDF) that generates the combustion air and the induced draft fan (IDF), which exhausts the flue gas into the atmosphere, together consume at least 40% of the total power [4]. The higher heating value of the dry sludge is 16–21 MJ/kg. However, because the de-watered sludge contains about 80 wt.% moisture, the high temperature flue gas is used only for heat exchange. Additionally, the nitrogen content of the sludge is considerably higher than that of other fuels, such as coal and wood. Thus the emissions of NO_x and N_2O are anticipated to be high. The global warming potential of N_2O is 310 times that of CO_2, so the emission of N_2O is a big problem.

Besides incineration there are other techniques for sewage sludge treatment such as gasification and fermentation, which produce a gas that is rich in H_2 and/or CH_4, which can in turn be used in a gas engine to generate electricity. In other words, the purpose of these technologies is to convert the organic material in the sludge into energy. However, gasification produces tar simultaneously with gas, so this processing is complex and costly [5–8]. On the other hand, the heating value of the digested sludge after fermentation is so low that a large amount of supplementary fuel is needed for incineration [9].

To reduce power consumption and to recover energy from sludge, we have proposed a new design of a fluidized bed incinerator equipped with a turbocharger (Fig. 2). The major differences between our proposed incinerator and the conventional one shown in Fig. 1 are that ours uses a pressurized combustor and that a turbocharger is used in the subsequent stage. Our plant has four main advantages. (1) The combustion rate can be improved because the oxygen partial pressure in the combustor is increased by the pressurization. The incinerator

---

* Corresponding author. Tel.: +81 29 861 8624; fax: +81 29 861 8209.
E-mail address: takahiro-murakami@aist.go.jp (T. Murakami).

0378-3820/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.fuproc.2009.03.003

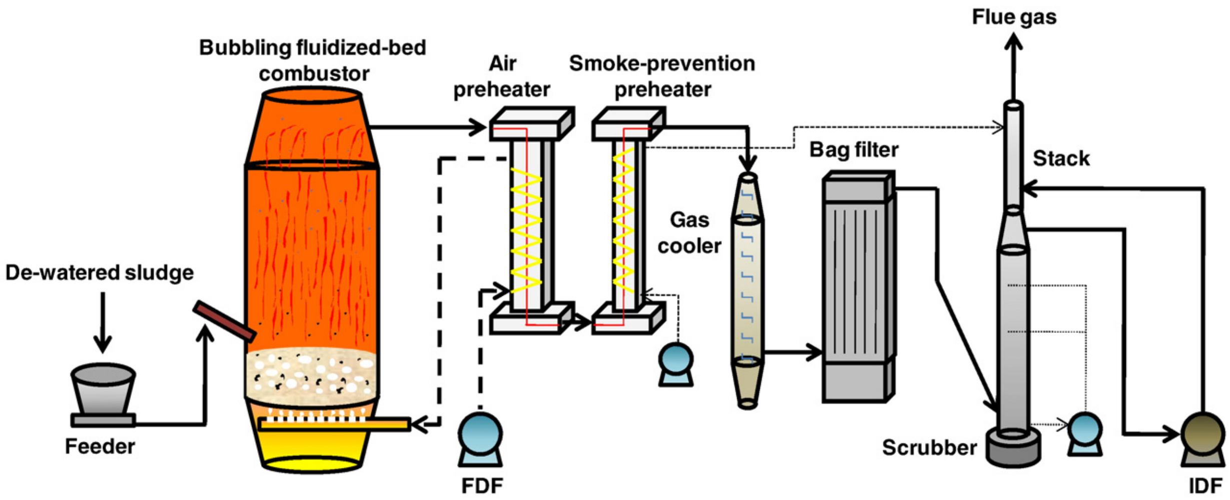

Fig. 1. Schematic diagram of a conventional incineration plant, which is equipped with an atmospheric bubbling fluidized bed combustor.

volume can be substantially smaller than that of an atmospheric incinerator with the same incineration capacity. Thus, the amount of supplementary fuel can be reduced because the heat loss from the incinerator can be reduced. (2) Because the maximum operating pressure is 0.3 MPa (absolute pressure), which matches the pressure required for the turbocharger, a pressure vessel is unnecessary. Therefore, the material cost of plant construction can be reduced. (3) An energy savings of more than 40% can be achieved compared with a conventional plant, and consequently CO_2 emissions originating from power generation can be reduced because the FDF and the IDF are unnecessary. (4) Because steam in the flue gas becomes the working fluid of the turbocharger, the turbocharger can generate surplus air in addition to the combustion air. The surplus air can be used in other processes, such as aeration, in sewage works. This new design positively utilizes the sludge moisture, which until now has been considered negatively. Therefore, our proposed design will not only save energy but also generate energy.

A demonstration plant (4.32 t/day scale) at a sewage works in Oshamanbe Cho in Hokkaido was constructed, and in this report, we describe the operation and combustion characteristics of this plant. The objectives of this work were to obtain the design data for a commercial plant and to compare our proposed plant and a conventional one using the experimental results.

2. Experimental

The constructed demonstration plant (Fig. 3) consisted of a fuel feeder, a pressurized bubbling fluidized bed combustor, an air preheater, a ceramic filter, a turbocharger, and a stack. The combustor was 700 mm in internal diameter and 9200 mm in height. The temperatures (T_1–T_6) were measured by thermocouples located at heights above the distributor: 300 and 600 mm in the bed and 1300, 3000, 4600, and 6800 mm in the freeboard. The bed material was a mixture of quartz sands with mean diameters of 400 and 700 μm. The fluidized bed height during operation was about 950 mm. The turbocharger, which had been designed and manufactured for the use with a diesel engine on a motor truck, had the following specifications: weight, 10.5 kg; outlet air flow rate, 120–900 $m^3{}_N/h$; maximum pressure ratio, 3.0; and maximum operating temperature, 1023 K. The fuel properties are listed in Table 1. The as-received sludge moisture content was 87.0 wt.%, and the nitrogen content on dry basis was 7.50 wt.%; these values are considerably higher than those of the

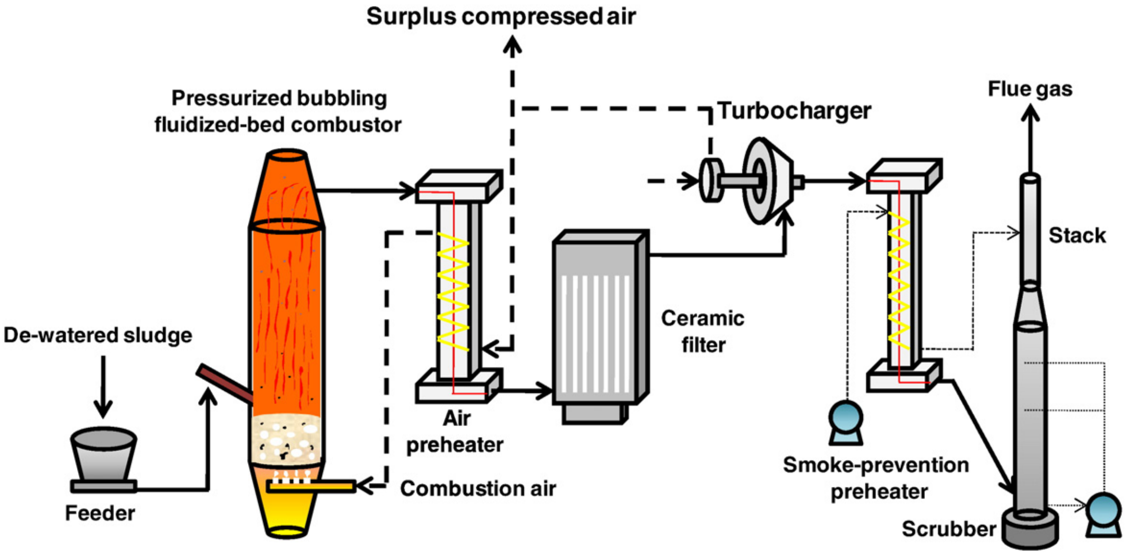

Fig. 2. Schematic diagram of the proposed plant, which is equipped with a pressurized bubbling fluidized bed combustor coupled with a turbocharger.

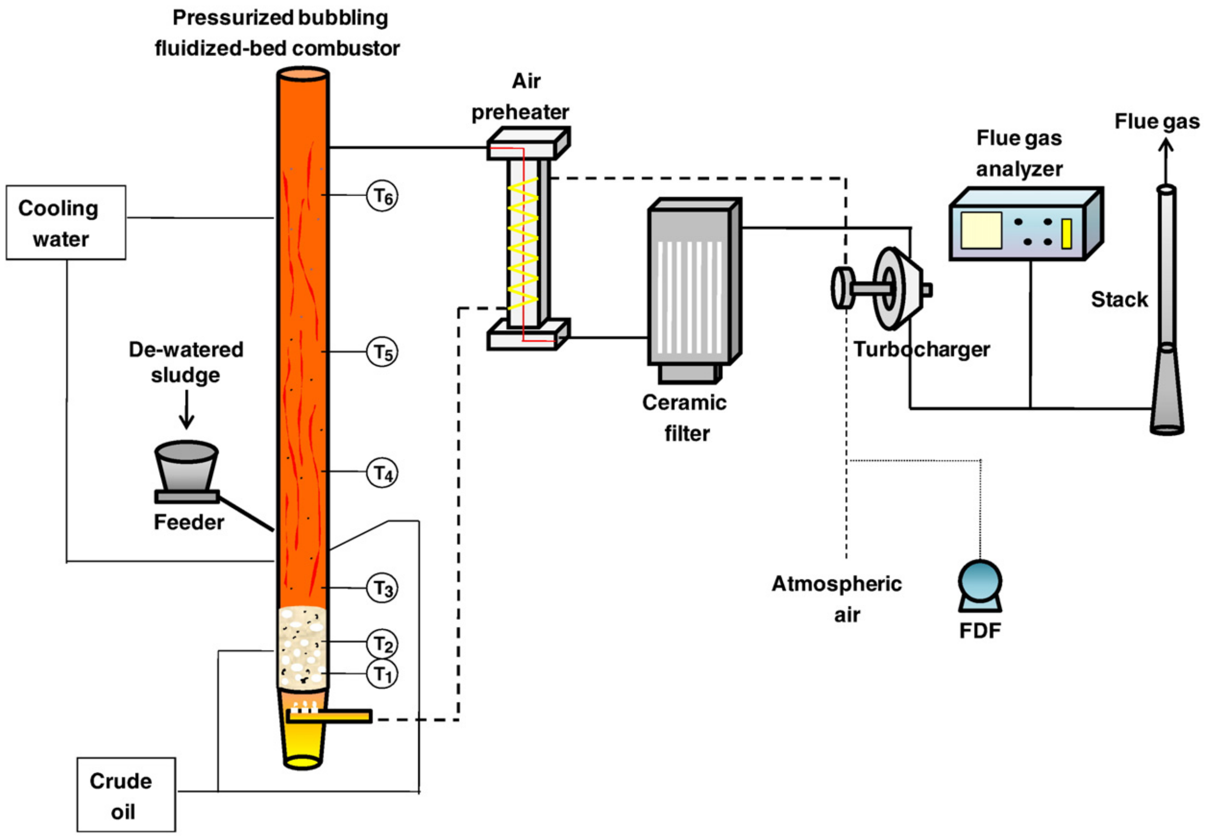

Fig. 3. Schematic diagram of the demonstration plant. T in this figure shows a thermocouple.

other solid fuels. The higher heating value was 20.1 MJ/kg (d.b.), which is within the range for typical sewage sludge. The sludge properties were analyzed for each experiment.

During the start-up, the combustor temperature was increased by supplying the combustor with crude oil at a supply point 1750 mm above the distributor. The fuel supply point was changed to the bed at 500 mm when the temperature exceeded 873 K. During the start-up period, the turbocharger was driven by air from the FDF. The air from the turbocharger was supplied to the bottom of the bed through a distributor. When the inlet gas temperature of the turbocharger exceeded 623 K, the FDF was stopped, and the system simultaneously became self-sustaining; that is, all the combustion air was generated by the turbocharger driven only by the flue gas. De-watered sludge was continuously supplied through the fuel feeder at 2100 mm when the bed temperature exceeded 1073 K. Cooling water was injected into the combustor at 1500 and 6000 mm when the temperature of the air preheater exceeded 1123 K. This temperature depends on the heat-resistant temperature of the material used. The flue gas was exhausted from the stack into the atmosphere after passing through the air preheater, the ceramic filter, and the turbocharger. Heat exchange between the combustion air generated by the turbocharger and the high temperature flue gas occurred in this preheater. The ceramic filter at the subsequent stage mainly removed dust.

Table 1
Sewage sludge properties.

Moisture [wt.%]		87.0
Ignition loss [dry, wt.%]		85.0
Ultimate analysis [dry, wt.%]	C	43.7
	H	6.84
	N	7.50
	S	0.96
	O	26.1
Higher heating value [MJ/kg (d.b.)]		20.1

The sludge feeding rate was 180–190 kg/h. The mean combustor temperature was 1019–1075 K in the bed and 1138–1205 K in the freeboard. The absolute combustor pressure was about 0.2 MPa. The air ratio was about 1.60 based on the oxygen concentration in the flue gas. The U_o/U_{mf} ratio (the ratio of the superficial gas velocity and the minimized fluidized velocity) was about 6.0. The O_2, CO, CO_2, and NO_x concentrations in the flue gas were analyzed with continuous gas analyzers (IR400 Yokogawa Elec. Corp., Tokyo, Japan; VA-3000 HORIBA, Ltd., Kyoto, Japan), and N_2O concentration was measured with a gas chromatograph (CP-4900 Varian Inc., California, U.S.A.). Gas samples were extracted at the stage subsequent to the turbocharger. Most data were recorded at 1-min intervals by a logger, but data for N_2O were taken only every 10 min.

3. Results and discussion

3.1. Operation characteristics

The fuel feeding rate, combustor temperature (in the freeboard and in the bed), pressure, inlet air flow rate, and flue gas flow rate were steady throughout 5 h of continuous operation (Fig. 4). The steady operation exceeded 600 h in total. However, only about 70% of the inlet air flow rate for the combustor could be supplied by the turbocharger driven by flue gas; the other 30% was supplied by the FDF. The FDF was required because the heat loss from each auxiliary was high. For example, the outlet gas temperatures at the combustor, air preheater, and ceramic filter were 1071, 823, and 694 K, respectively; the heat loss at each step was much greater than 10%. The inlet gas temperature of the turbocharger was only 651 K. According to the design specifications of the turbocharger, if the inlet gas temperature can be maintained at 873 K, the turbocharger can

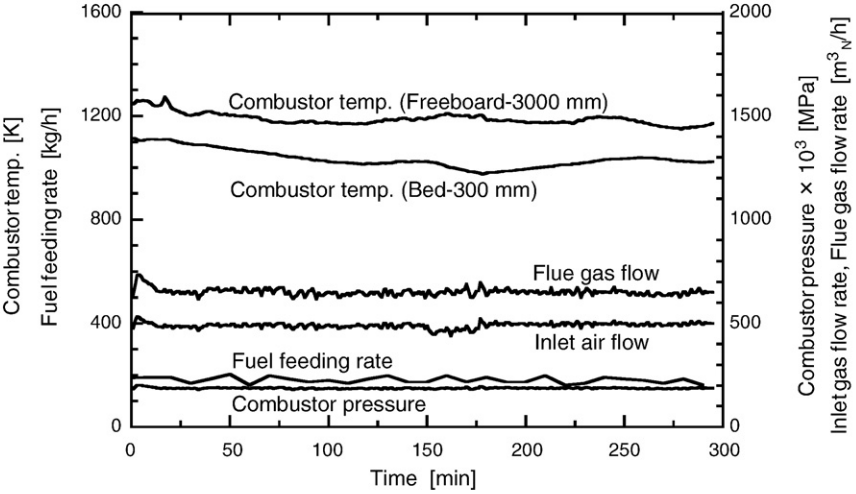

Fig. 4. Typical change of operation parameters with time during a continuous combustion test in the demonstration plant.

generate not only enough air for sludge combustion but also 60 $m^3{}_N$/h of surplus compressed air. The heat loss from each auxiliary at a commercial plant (100 t/day scale) is less than 5.0% [4]. Therefore, the FDF and the IDF are unnecessary at the commercial scale because the efficiency of turbocharger is expected to be improved by scale-up. No operation-limiting problems were encountered with the other auxiliaries. Blockage of ceramic filter by adhesion of alkali and ash particles was not observed, and only a periodic back wash reverse filtration can be needed to clean the filter. Corrosion in the turbocharger by sulfur in the flue gas was not observed because the operating temperature was higher than the dew point of SO_x. However, because the temperature of the turbocharger decreases during the stop operation, such as a periodic check of the plant, it is necessary to switch the working fluid from the flue gas to air. Undesirable trace gas species, which includes heavy metal, in the flue gas can be removed by the conventional method using caustic soda in the scrubber.

3.2. Temperature distribution in the combustor

The temperature distribution in the combustor was also clarified (Fig. 5). The temperatures of the two points in the bed were the lowest and were almost the same. This result suggests that drying and pyrolysis of the fuel occurred mainly in the bed. The low temperature at these points was due to the latent heat of moisture during drying and to the endothermy of the pyrolysis reaction. In contrast, the temperature 3000 mm above the distributor, corresponding to the freeboard, was the highest. It is thought that the pyrolysis gas burned in this region, causing the temperature to rise.

3.3. Flue gas characteristics

Because N_2O emission in conventional incinerators is a big problem, the flue gas characteristics of our plant were elucidated. Fig. 6 shows the relationship between the CO, NO_x, and N_2O emissions and the O_2 concentration in the flue gas (The gas emissions were corrected at an O_2 concentration of 12% in the flue gas, which is a usual calculation method for Japanese incinerators [1,2].). CO emission increased slightly with decreasing O_2 concentration, and low CO emission was maintained under all experimental conditions. The combustion rate was improved by the increase in the combustor oxygen partial pressure due to the pressurization. Additionally, the temperature decreased from 3000 mm to the exit (Fig. 6), so that the combustor had sufficient gas residence time for CO combustion. NO_x emissions tended to increase with decreasing O_2 concentration. This tendency, which was also reported for atmospheric bubbling fluidized bed combustor of wet sludge [10], is opposite to the trend of other fuels such as coal, wood, and dry sludge [10–12]. In addition, these emissions were lower than that observed for coal combustion [13–15]. The moisture content in the sludge was so high that the steam partial pressure was also high. In addition, pressurization facilitates the generation of O and OH radicals in the reactive zone of the combustor, and these radicals inhibit NO formation reaction [16]. This phenomenon will be verified by kinetic calculations in future studies. N_2O emission changed little even when the O_2 concentration changed substantially. The dependence of N_2O emission on freeboard temperature in an atmospheric combustor has been reported [10]. In our study, N_2O emission decreased with increasing freeboard temperature (Fig. 7). Therefore, N_2O emission can be arranged by the temperature when a fuel with the high nitrogen content is burned under pressurized conditions.

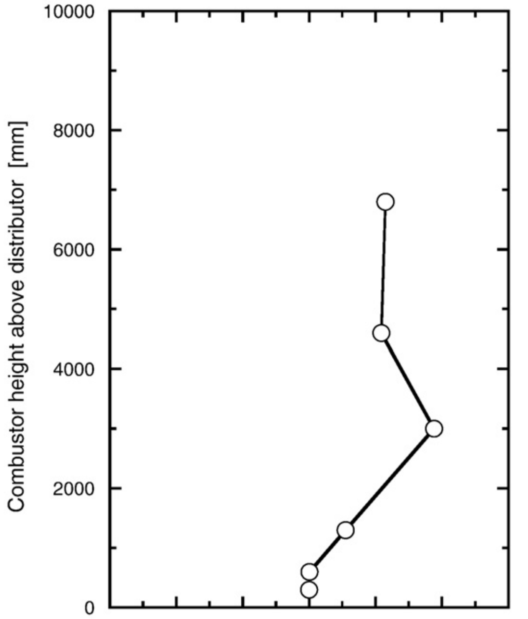

Fig. 5. Temperature distribution in the combustor (fluidized bed height, 950 mm).

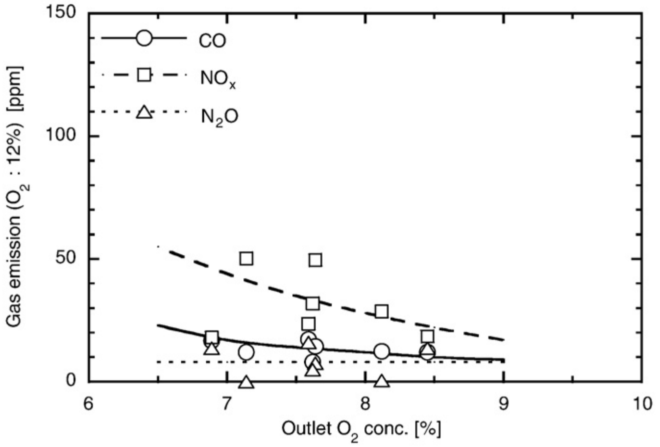

Fig. 6. Relationship between CO, NO_x, and N_2O emissions and O_2 concentration in the flue gas.

3.4. Comparison of the proposed plant and a conventional plant

CO_2 emissions and the cost of the proposed plant and a conventional plant were compared at an incineration capacity of 100 t/day. Because two fans and a feed water pump, which is used by gas cooler, can be omitted in the pressurized plant, electric power consumption is reduced by about 50% (from 350 to 180 kW) (Table 2). Operation at 0.3 MPa can permit reduction of the combustor volume by 1/3 in comparison with a conventional combustor, which operates at 0.1 MPa. This volume reduction led to a reduction in the combustor air requirements for the same incineration capacity. Thus, heat loss is greatly reduced, and the amount of supplementary fuel is reduced by about 25% (from 54 to 40 L/h). CO_2 emissions originating from electric power consumption and supplementary fuel were calculated using CO_2 emission indexes of 0.555 t-CO_2/MWh for electric power and 2.71 kg-CO_2/L for crude oil [17] (Table 2). The calculation indicated that CO_2 emissions can be reduced by about 1000 t/year/commercial plant over 300 days of operation, which corresponds to an approximately 40% reduction over a conventional plant. Sewage plants emitted 7 million t (CO_2 conversion value) of greenhouse gases in 2004 [1,3]. Therefore, the utilization of our new design would reduce CO_2 emissions by 0.014%/plant. In addition, the cost of fuel and electricity for our plant would be 23 million yen less than that of the conventional plant (Table 2) (We used values of 12 yen/kWh for electric power and 80 yen/L for crude oil to do these calculations [4].).

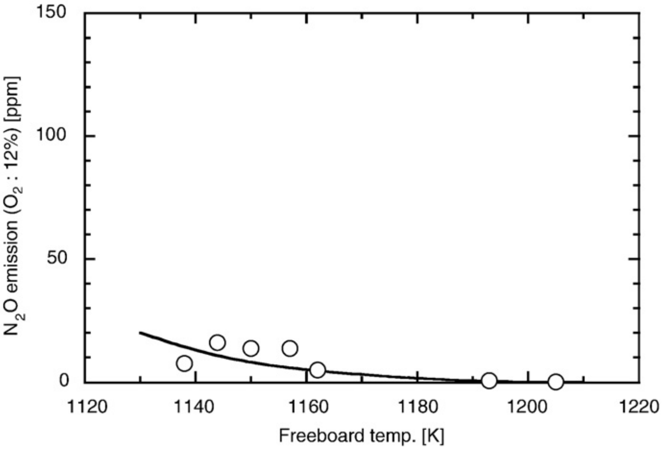

Fig. 7. Dependence of N_2O emission on freeboard temperature.

Table 2
Comparison of parameters for the proposed and conventional plants.

	Conventional	Proposed
Electric power consumption by the auxiliaries [kW]	350	180
CO_2 emissions [ton-CO_2/year]		
Electric power consumption	1399	714
Supplementary fuel	1054	780
Fuel and electric costs [million yen/year]		
Electric power consumption	30.2	15.6
Supplementary fuel	31.1	23.0
CO emission (O_2:12%) [ppm]	50	13.3
NO_x emissions (O_2:12%) [ppm]	100	31.5
N_2O emission factor [g-N_2O/t-de-watered sludge]	645	280

The flue gas concentrations for the proposed and conventional plants were also compared (Table 2) [4,18]. CO and NO_x emissions in the proposed plant were less than half of those in the conventional one, owing to the effect of pressurization. The N_2O emission factor, which is the amount of N_2O emitted from 1 t of de-watered sludge and used the emission factor at 1123 K (mean freeboard temperature) [19], of the proposed plant was less than half of that of the conventional plant (Table 2). It is thought that N_2O was decomposed at a local high temperature zone in the freeboard. This phenomenon in future studies by investigating the chemical reaction rates using a simulation package will be verified. In addition, moisture load in the bed was about 300 kg-mois/t-sand•h in this experiment. The loading for an atmospheric combustor is about 150 kg-mois/t-sand•h [4, 18]. Thus, pressurization allowed us to double the load so that more moisture can be used as a working fluid of the turbocharger. Our results indicate that utilization of the proposed design reduce the environmental impact of CO, NO_x, and N_2O emissions.

In the future, we plan to elucidate the co-firing characteristics of sludge and biomass such as unutilized wood and weed, which are abundant in Hokkaido. The aim is to decrease the use of supplementary fuel such as crude oil by stabilizing the bed temperature.

4. Conclusions

The operation and combustion characteristics of sludge were clarified for a new type of incineration plant consisting of a pressurized fluidized bed combustor coupled with a turbocharger. The performance of our proposed plant and that of a conventional plant were compared, and the following results were obtained. The operation was stable for a long time. Because the FDF, the IDF, and the feed water pump can be eliminated in the proposed plant at an incineration capacity of 100 t/day, an energy savings of approximately 50% can be achieved compared with a conventional plant. Additionally, the amount of supplementary fuel can be reduced by about 25% because of the pressurization. Hence, CO_2 emissions can be reduced by about 1000 t, and 23 million yen can be saved. In our plant, drying and pyrolysis of the fuel occurred mainly in the bed, and the pyrolysis gas burned in bottom zone of the freeboard. CO NO_x, and N_2O emissions were substantially reduced by the pressurization. N_2O emission could be controlled by the freeboard temperature in spite of the high nitrogen content. Therefore, the proposed fluidized bed incinerator with the turbocharger can achieve not only energy recovery but also a low environmental impact.

Acknowledgement

This work was conducted as part of a research program financed by the New Energy and Industrial Technology Development Organization (NEDO), Japan, on developing a technology for high-efficiency conversion of biomass energy.

References

[1] Japan Sewage Works Association, Investigation report for the current status of the sludge treatment in 2004, 2007, [in Japanese].
[2] Ministry of the Environment, Investigation report for the exhaust and treatment of the industrial waste in 2004, 2007, [in Japanese].
[3] Ministry of Land, Infrastructure and Transport Japan, Investigation report for battle against global warming on the sewage system field in 2004, 2007, [in Japanese].
[4] Sanki Engineering Co., Ltd., Tsukishima Kikai Co., Ltd., PWRI, 2005–2007 NEDO report for developing a technology of high efficiency conversion of biomass energy, 2008, [in Japanese].
[5] J.J. Manya, J.L. Sanchez, J. Abrego, A. Gonzalo, J. Arauzo, Influence of gas residence time and air ratio on the air gasification of dried sewage sludge in a bubbling fluidized bed, Fuel 85 (2006) 2027–2033.
[6] T. Murakami, T. Suda, S. Mouri, J. Shigeta, T. Hirata, T. Fujimori, W. Huang, Co-gasification of sewage sludge and plastic wastes: evaluation of experiment and application, J. Jpn. Inst. Energy 85 (2006) 964–970, [in Japanese].
[7] T. Murakami, G. Xu, T. Suda, Y. Matsuzawa, H. Tani, T. Fujimori, Some process fundamentals of biomass gasification in dual fluidized bed, Fuel 86 (2007) 244–255.
[8] A. Adegoroye, N. Paterson, X. Li, T. Morgan, A.A. Herod, D.R. Dugwell, R. Kandiyoti, The characterization of tars produced during the gasification of sewage sludge in a spouted bed reactor, Fuel 83 (2004) 1949–1960.
[9] R.M. Worden, A.J. Grethlein, M.K. Jain, R. Datta, Production of butanol and ethanol from synthesis gas via fermentation, Fuel 70 (1991) 615–619.
[10] M. Sanger, J. Werther, T. Ogada, NO_x and N_2O emission characteristics from fluidized bed combustion of semi-dried municipal sewage sludge, Fuel 80 (2001) 167–177.
[11] J.R. Pels, M.A. Wojtowicz, F. Kapteijn, J.A. Moulijn, Trade-off between NO_x and N_2O in fluidized-bed combustion of coals, Energy Fuels 9 (1995) 743–752.
[12] B. Leckner, Fluidized bed combustion; mixing and pollutant limitation, Prog. Energy Combust. Sci. 24 (1998) 31–61.
[13] B. Leckner, L.E. Amand, K. Lucke, J. Werther, Gaseous emissions from co-combustion of sewage sludge and coal/wood in a fluidized bed, Fuel 83 (2004) 477–486.
[14] K. Svoboda, M. Pohorely, Influence of operating conditions and coal properties on NO_x and N_2O emissions in pressurized fluidized bed combustion of subbituminous coals, Fuel 83 (2004) 1095–1103.
[15] A.T. Atimtay, B. Kaynak, Co-combustion of peach and apricot stone with coal in a bubbling fluidized bed, Fuel Process. Technol. 89 (2008) 183–197.
[16] M. Shoji, T. Yamamoto, S. Tanno, H. Aoki, T. Miura, Modeling study of homogeneous NO and N_2O formation from oxidation of HCN in a flow reactor, Energy 30 (2005) 337–345.
[17] Ministry of the Environment, Guide Line for Calculation Method of Total Emissions of Greenhouse gas, 2007, pp. 1–71, [in Japanese].
[18] H. Honda, Advanced incinerator using sewage sludge, Glob. Environ. 2 (2001) 98–102 [in Japanese].
[19] Japan Institute of Wastewater Engineering Technology, Global Warming and Inventory, 2007, [in Japanese].