Development of an advanced sewage sludge incinerator, "turbocharged fluidized bed incinerator"

— The role of AIST in the development of a new system —

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Annual production of sewage sludge in Japan has increased, and most of the sewage sludge is incinerated. With conventional sewage sludge incinerators, a large amount of energy is needed for operation. Additionally, the emissions of greenhouse gas N_2O are expected to be high, because sludge contains a high concentration of nitrogen. In this R&D, an advanced sewage sludge incinerator "turbocharged fluidized bed incinerator," which can achieve not only energy savings but also a low environmental impact, was proposed in collaboration with Public Works Research Institute and companies. This new system consists of a pressurized fluidized bed combustor coupled with a turbocharger. The R&D to achieve practical use of the proposed system is primarily explained in this paper.

Keywords **:** Sewage sludge, incinerator, pressurized fluidized bed, turbocharger, energy recovery

1 Introduction

With the spread of the sewage treatment system, the amount of sewage sludge is increasing yearly in Japan, and most is incinerated. The sewage sludge after dewatering still contains about 80 % water. Currently, it is incinerated using large amount of supplementary fuel such as gas and fuel oil, and therefore, the sewage sludge incineration process is actually an energy consuming process. In addition, sewage sludge contains extremely high amount of nitrogen compared to other solid fuels such as coal or biomass, and large amounts of nitrogen oxide (NO*x*) and nitrous oxide (N_2O) are produced during incineration. In general, while the NO*x* concentration increases as the combustion temperature increases, the N_2O concentration decreases. Particularly, the global warming potential of N_2O, a greenhouse gas, is 310 times higher than CO_2, and the emissions of such gases are a matter of grave concern.

Currently, of the greenhouse gases (in CO_2 equivalent) emitted from the sewage plants, the emission of N_2O produced during sludge incineration dominates about one-fourth. Increasing the incineration temperature is attempted as a method to reduce the N_2O. The N_2O production is known to be inhibited at high temperature, and the N_2O emissions can be reduced to about 60 % by incineration at high temperature of 850 °C, which is 50 °C higher than the conventional operation temperature of 800 °C. Most of the sewage sludge incinerators in Japan were constructed during the 1980s to 1990s, and the incinerators have progressively aged. High temperature that may damage the incinerator cannot be used in many systems. Therefore, the Ministry of Land, Infrastructure Transport and Tourism (MLIT) has proposed measures for energy savings and greenhouse gas reduction in the sewage sludge incineration process,[1] and a system that essentially achieves both energy savings and low N_2O production is in demand. In the future, the need for updating a large number of the existing incinerators is expected, and the development of a sewage sludge incineration process using a new technology is an immediate issue.

A typical flow sheet of conventional sewage sludge incineration system is shown in Fig. 1. As shown in the figure, fluidized beds are often used in sludge incineration. Silica sand is usually used as a bed material. By supplying air from underneath the gas distributer plate, silica sand is fluidized with bubbles like when the water is boiling. The sand acts as the heat medium, and the dewatered sludge with high water content can be incinerated at stable temperature in the fluidized bed. The sewage sludge contains about 80 % water, and supplementary fuel (utility gas, fuel oil, etc.) is used to maintain the temperature within the incinerator. A fluidized bed incinerator is roughly divided into the sand bed (fluidized bed) and the freeboard that is mainly gaseous space on the upper part of the bed. Drying and pyrolysis of the sludge occur mainly in the sand bed. Next, combustible gas produced by pyrolysis in the bed burns in the freeboard. Flue gas is released into the atmosphere as clean gas after passing through the treatment system. In the conventional incineration system, two fans are needed for the operation. One is the fan to supply air for sludge incineration, and the other is the fan to induce flue gas from sludge incineration. The power

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to drive these two fans is said to dominate about 40 % of the energy needed for the entire system, and these fans are major causes of electricity-derived CO_2 emissions for which energy-saving measures must be taken.[2]

Through the joint development of AIST, the Public Works Research Institute (PWRI) of MLIT, and some private companies, a new incineration system as shown in Fig. 2 was proposed to raise the energy-saving capabilities and to decrease the N_2O emissions of the sewage sludge incinerator.[2][3] A unique characteristic of this system is that the fluidized bed incinerator is operated under pressurized conditions, and the generated high-temperature, high-pressure flue gas can be used to drive a turbocharger installed in the downstream of the incinerator to produce the combustion air. This system has the following advantages compared to the conventional system (Fig. 1).

1) Since combustion proceeds in the pressurized condition, the incinerator volume can be reduced for the same incineration capacity. This allows the reduction of heat loss from the incinerator, and the amount of necessary supplementary fuel can be reduced.

2) Since the combustion air can be produced by the turbocharger, the air supply fan is not needed. Also, since the flue gas can be released into the atmosphere by residual pressure from the pressurized operation, the induced draft fan is unnecessary. The two fans that are major power consumers can be eliminated, and power consumption can be reduced greatly compared to the conventional system. Moreover, the excess air can be used for aeration in the sewage works.

3) Since energy recovery is done within the turbocharger, the equipment is simpler compared to the one using a gas turbine. For matching with the turbocharger, operation pressure of only about 0.25 MPa is needed, and high-pressure operation and the expensive pressure vessel required to match with the gas turbine are not necessary.

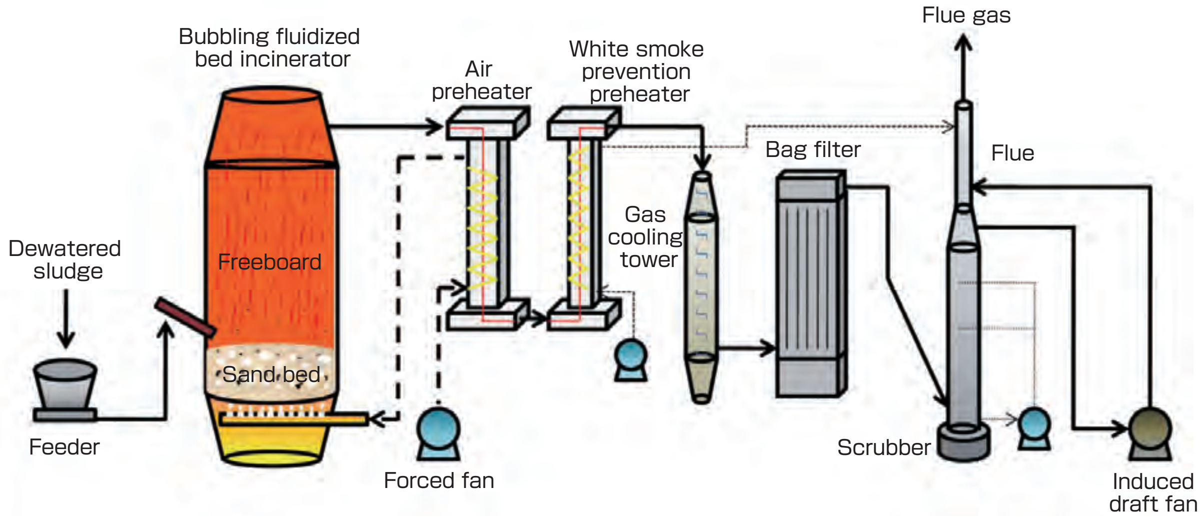

Fig. 1 Typical flow diagram of the conventional sewage sludge incineration system

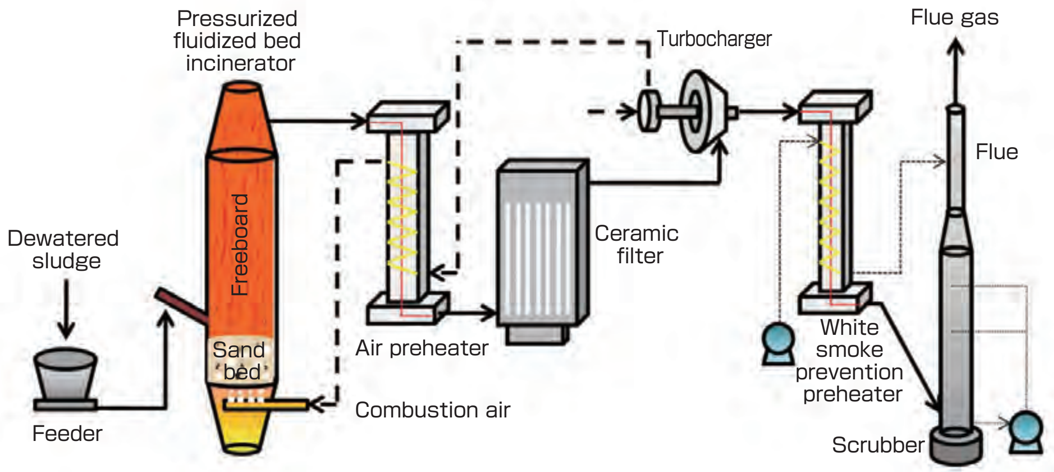

Fig.2 Flow diagram of the turbocharged fluidized bed incineration system

We named this next-generation sewage sludge incineration system the "turbocharged fluidized bed incineration system," and conducted R&D with the goal of putting this system to practical use.

2 Scenario to realize the goal

The goal of this R&D is to realize a turbocharged fluidized bed incineration system as mentioned in the previous chapter. The average size of sewage sludge incinerators in Japan is that which can manage 100 t/d of sludge supplied to the incinerator. To commercialize such a large-scale plant with new technologies, it is necessary to conduct fundamental research using laboratory-scale experimental facilities, followed by demonstration research at a scaled-up demonstration plant based on the results of the fundamental research. Since several years are necessary to achieve each step, long-term R&D is necessary for practical application, just as in general process development. In this chapter, the road to commercialization will be explained.

In 2000, to plan the essential technological innovation for the sludge incinerator, PWRI established a research group jointly with private companies. In one of the research group sessions, a power generation technology combined with pressurized fluidized bed combustion was taken up as a new high-efficiency power generation method for coal and for which practical application was in progress. The sewage sludge could be easily transported to the pressurized system via a high-pressure pump, there was no problem in continuous supply, and the match with pressurized fluidized bed incineration was good. After studying the system, it was confirmed that there was a possibility for achieving dramatic energy savings by recovering the energy from the high-temperature, high-pressure combustion gas. However, in the field of sewage sludge or waste incineration, there was absolutely no experience with the pressurized fluidized bed incineration, and the development of a new system applying this type of incineration technology by PWRI and the incinerator manufacturer was difficult.

During this time, concern for greenhouse gas was increasing, and at the research institutes in Tsukuba, the research on estimating the greenhouse gas inventory was conducted across the ministries and agencies, with the leadership of the Ministry of Environment. In this project, AIST was in charge of the greenhouse gas emissions in the combustion process of fossil fuels, and we also assisted the measurement of N_2O gas emissions from the sewage sludge incinerator that was mainly been done by PWRI.[4] At the time, AIST's main research topic was the pressurized fluidized bed combustion of coal, and through exchanges with the people of PWRI, we found that our initial research might satisfy their demands, and this led to the official request for joint research from the PWRI research group. This was the beginning of the research, and it was a technological development in which the characteristic of Tsukuba, where several research institutions are concentrated, was fully utilized.

There were two institutions that participated in the development, AIST and PWRI. The division of roles was clear from the beginning. AIST was in charge of the technical support in conducting the research, while PWRI was in charge of the technological evaluation and the PR activities to the local governments and companies. There were three private companies that initially participated in the joint research: Tsukishima Kikai Co., Ltd., Kubota Corporation, and IHI Corporation. In addition to the manufacturer of sewage sludge incineration plants, we collaborated with a gas turbine manufacturer that could sufficiently understand the basic concept of the research and also manufactured turbochargers. We started from independent research by these five parties. In conducting the independent research, we were about to obtain results for the basic research and the optimization of the system design using the new technologies. However, due to various reasons related to the economic situation in Japan, all the companies except Tsukishima Kikai withdrew from the joint research in 2005. Sanki Engineering Co., Ltd. that considered this technology highly joined, and a new start was kicked off with four parties including AIST and PWRI. A demonstration plant was constructed and operated after obtaining external funding, to confirm the durability performance by long-time operation of the demonstration plant. The process was thus completed.

Yet, the introduction of a new process without performance achievements was a cause of concern for users, and the completion of the process did not lead immediately to practical use. Therefore, the technical PR to the local governments, the main users of this system, was done by PWRI that had close relationships with the sewage administrators. As a result, the technology was highly acclaimed by the people concerned, but this did not lead to immediate employment.

As a result of considering the strategies for practical application within the development group, we reached the conclusion that it would be most effective to get the Tokyo Metropolitan Government, which leads Japan in the sewage public work, employ this process. At the time, the Bureau of Sewage, Tokyo Metropolitan Government was planning to reduce greenhouse gas emissions from sewage treatment (Earth Plan), and we conducted PR activities for this technology by concentrating on the energy saving and low N_2O characteristics. While we obtained understanding of the person in charge, a confirmation test would be done jointly with Tokyo for the long-time durability that was the greatest barrier in actually employing the new system. Ultimately, the goal was met, the system was registered as the main technology of Tokyo's Earth Plan, and we received an order for the commercial unit.

3 Synthetic method to achieve the objective

3.1 Laboratory-scale pressurized fluidized bed incineration test

As mentioned in the previous chapter, this research started from independent research, and during that time, AIST was in charge mainly of the pressurized incineration experiment of the sewage sludge, while the private companies and PWRI were in charge of the optimal design for the turbocharged fluidized bed incineration system for sewage sludge. There was no combustion data under pressurized conditions for the sewage sludge. Therefore, the experiment was started by installing a bubbling fluidized bed incinerator for sewage sludge incineration and a high-pressure sludge pump for supplying sewage sludge to the testing equipment for pressurized combustion owned by AIST, as shown in Fig. 3.

The schematic diagram of the whole system is shown in Fig. 4.[5][6] The pressure vessel was originally designed and manufactured for the pressurized combustion experiment of coal. It was made of stainless steel, with an inside diameter of 1,200 mm, height of 3,200 mm, and designed pressure of 0.99 MPa. A bubbling fluidized bed incinerator (diameter of 80 mm, height of 1,300 mm) was installed inside the vessel, to maneuver the sludge supply, air supply, electric furnace, and others during the experiment, and the control device was installed outside the pressure vessel. The sludge was supplied continuously through a vertical tube on the uppermost part of the fluidized bed. One-touch connector was used for the joint that connected the sludge supply tube to the pressure vessel or the fluidized bed, considering the preparation before the experiment and cleanup after the experiment. To homogenize the sludge property during the experiment, 10-20 kg of sludge was mixed in the mixing tank of the high-pressure sludge pump for pre-experiment preparation. Water was added to improve fluidity of the sludge (Fig. 5).

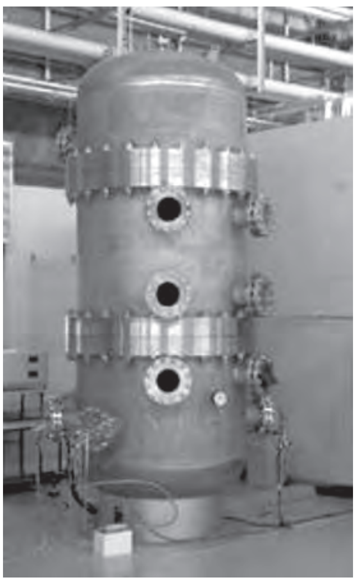

Fig. 3 Photograph of the pressure vessel

Table 1. Analytical values of the sewage sludge

Proximate analysis [wet, wt.%]	Water content	78.0
	Volatile content	13.9
	Fixed carbon	1.8
	Ash content	6.3
Ultimate analysis [dry, wt.%]	C	29.8
	H	4.0
	N	5.0
	S	1.1
	O	21.4
Higher heating value [MJ/kg (dry)]		17.10

Table 2. Example of the composition of sludge incineration ash

Ash composition [dry, wt.%]	SiO_2	39.97
	Al_2O_3	10.88
	CaO	6.33
	MgO	2.57
	Fe_2O_3	3.78
	Na_2O	0.63
	K_2O	1.63
	P_2O_5	20.51

For the sewage sludge used as the experimental sample, the actual dewatered sludge was supplied for each experiment by the Ibaraki Prefectural Kasumigaura Regional Sewage Office. The properties of the dewatered sludge are listed in Table 1. Compared to fossil fuel, it has higher ash and nitrogen contents. The odor specific to sewage sludge was a problem, but measures against odor were taken by storing the dewatered sludge in a sealed container and thoroughly cleaning the high-pressure sludge pump and feed pipe after the experiments.

In the basic research, it was necessary to check whether there is melting of ash and the emission of NO*x* and N_2O that are environmental pollutants. The former is a phenomenon related to the foundation in establishing the process. The ash of the sewage sludge contains a large amount of alkaline component with low melting point, as shown in Table 2,[2] and there were concerns that in the pressurized incineration conditions, stoppage of fluidization caused by ash melting might occur in the local high-temperature region. The combustion experiment under maximum 1 MPa pressure was conducted, and as shown in the photograph of fly ash captured by a ceramic filter attached at the exit of the fluidized bed incinerator in Fig. 6, majority of the ash was fly ash with reddish brown color and no melting was observed.[5] Iron flocculant added to increase the sedimentation property of the sludge in the thickener might inhibit the melting of the alkaline component.

After confirming that the process could basically be established since ash melting could be avoided, the combustion characteristics during pressurized operation such as the temperature distribution in the incinerator and the effect of temperature on NO*x* and N_2O emissions were clarified. The N_2O emission decreased with the increase in combustion temperature, and the result obtained was the same as the known general findings of N_2O temperature dependency. On the other hand, the NO*x* emissions decreased compared to the combustion of coal or dried sewage sludge at the same temperature.[5] This was thought to be the inhibition effect of NO*x* production by steam that comprises about 40 % of the gas produced after incineration.[7] From these results, it was clarified that there was no significant deterioration in the emission properties upon incinerating the dewatered sludge under pressurized conditions, but rather, there was potential of reducing the environmental load.

3.2 System design

For the optimal design for the turbocharged fluidized bed sludge incineration system conducted by the private companies and PWRI, it was expected that the plant with advanced technology would be employed when updating the existing sludge incineration system, and investigations were done from the perspective of energy savings. For energy savings, the elimination of the two fans, one to supply combustion air and the other to induce flue gas after combustion, was necessary since they were major power consumers, and this could be achieved by introducing a pressurized system. As mentioned previously, the sludge contains high amount of water, and the steam content within the high-temperature flue gas is high at about 40 %. Therefore, when recovering the energy from high-pressure flue gas, the high-content steam can be used. To be able to efficiently use the flue gas characteristic of sludge that contains high amount of water for energy recovery is a

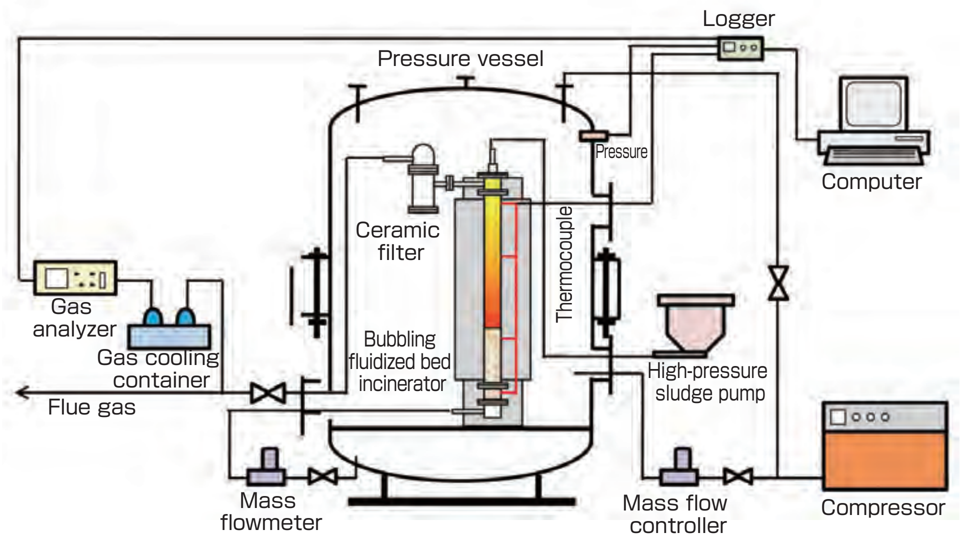

Fig. 4 Schematic diagram of the laboratory-scale pressurized fluidized bed incineration system

Fig. 5 Dewatered sludge supply by high-pressure sludge pump

Fig. 6 Photograph of the fly ash in the ceramic filter

major advantage. Moreover, in the pressurized system, the actual reactor volume becomes smaller than in atmospheric pressure when compared for the same capacity, as in general chemical plants. Therefore, the surface area of the incinerator is reduced, the amount of thermal radiation decreases, and the amount of supplementary fuel needed to maintain the combustion temperature can be reduced.

Normally, the method of manufacturing pressurized air using gas turbines is considered for the energy recovery from flue gas. However, the gas turbine that matched the flue gas volume of an incinerator having 100 t/d capacity that was our target must be specially ordered, since it was not of standard size, and it was found that the introductory cost and the maintenance cost would be extremely high. In addition, the optimal match with gas turbines required high pressure of over 1 MPa, and the incinerator must be installed in an expensive pressure vessel. From the above system analysis, we decided to abandon the pressurized combustion system using gas turbines.

As a solution, we decided to employ turbochargers that were more generally used compared to gas turbines. Combination with the turbocharger could be done at mild pressurized operation of maximum 0.25 MPa, and no pressure vessel was necessary. The pressure resisting structure of the incinerator would be simple, and the construction cost, necessary operators, and regular inspection were not so different from the conventional system. For the turbocharger that matched gas volume of 100 t/d capacity, a turbocharger for marine diesel engines already existed as a general-use product, and the introductory cost would be very reasonable.[2] From the above system considerations, the energy-saving “turbocharged fluidized bed incineration system” that could reduce both the CO_2 from power generation and the CO_2 from burning supplementary fuel was proposed, and a joint patent application was submitted.[8]

3.3 Demonstration test and practical use

Following the basic system design and the understanding of fundamental combustion property, it was necessary to build and demonstrate the proposed turbocharged fluidized bed incineration system. Therefore, we applied to the “Development of elemental technology for energy conversion to utilize the urban biomass collection system” of the New Energy and Industrial Technology Development Organization (NEDO), and fortunately, our proposal was selected. The construction site of the demonstration facility was the sewage plant site of Oshamanbe, Hokkaido where a demonstration circulating fluidized bed incinerator of Sanki Engineering was located. There, a plant of 5 t/d scale was constructed. The results of our basic research were applied to the design of this plant. The schematic diagram of the demonstration plant is shown in Fig. 7.[2][3] The pressurized incinerator with internal refractory structure was made of steel, with internal diameter of 700 mm and height of 9,200 mm. The turbocharger installed in the downstream of the fluidized bed incinerator was a general-use product installed in large diesel freight trucks, and the one of matching scale was installed in the demonstration plant. As a result, we succeeded in operation without the two fans that were used in the conventional system.[2][3]

From this phase, AIST was in charge of the setup of the gas analyzing system and the analysis of the operation results. As a result of conducting the continuous incineration test using actual sludge, it was found that the N_2O concentration in the flue gas was strongly dependent on the freeboard

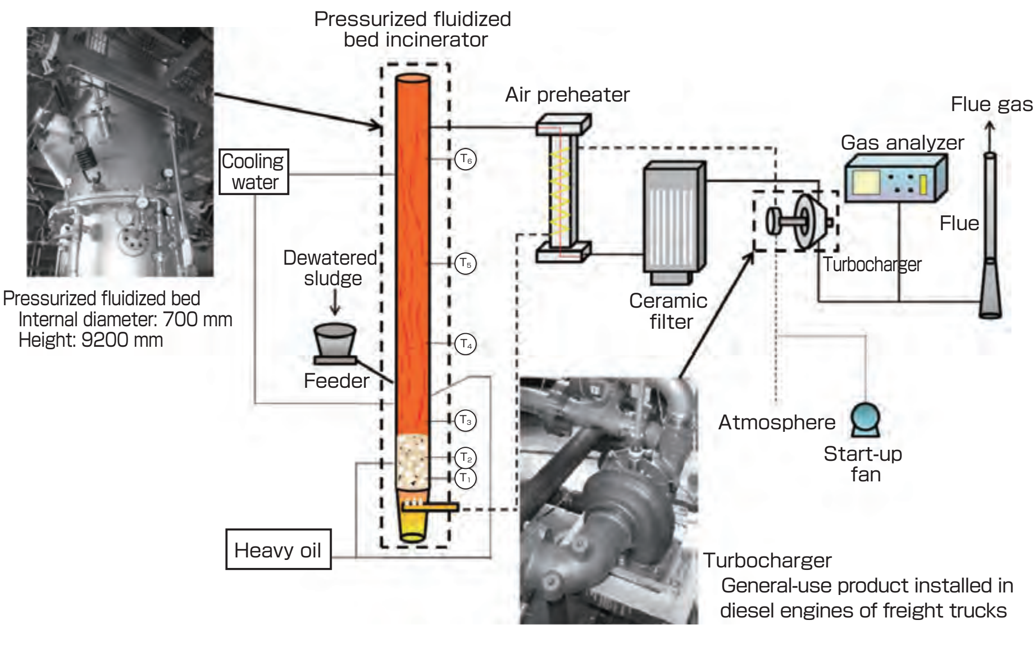

Fig. 7 Schematic diagram of demonstration plant

temperature, and the concentration decreased as the temperature increased, as shown in Fig. 8.[3] It was also found that the emission could be reduced to half compared to the high-temperature operation of the conventional system (Fig. 9).[3] AIST clarified the temperature dependency of N_2O emissions from the basic combustion experiment results, and from this experiment, focus was placed on the temperature distribution inside the incinerator of the demonstration plant. It was found from the analysis of the experimental results (Fig. 10)[6] that a local high-temperature region was formed in the lower part of the freeboard. The figure shows the results of comparing the temperatures of the atmospheric pressure operation and the exit temperature of the conventional system at about the same condition. In the pressurized operation, the combustion of the combustible gas generated by drying and pyrolysis of the dewatered sludge supplied to the fluidized bed occurs at the freeboard, similarly to the conventional type, but the combustion rates differ greatly. The local high-temperature region is formed at the lower part of the freeboard because of rapid burning of gases. In contrast, in the conventional atmospheric pressure operation, the combustible gas after pyrolysis burns evenly throughout the freeboard because the combustion rate of the gas is small, and the temperature increase is gradual. Therefore, the reduction in N_2O emissions at pressurized conditions in the turbocharged type should be because of the decomposition of N_2O in the local high-temperature region generated in the lower part of the freeboard.

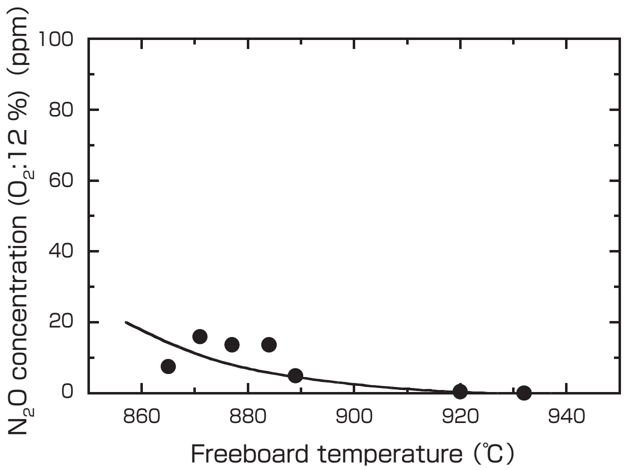

Fig. 8 Relationship between the N_2O concentration in flue gas and the freeboard temperature[9]

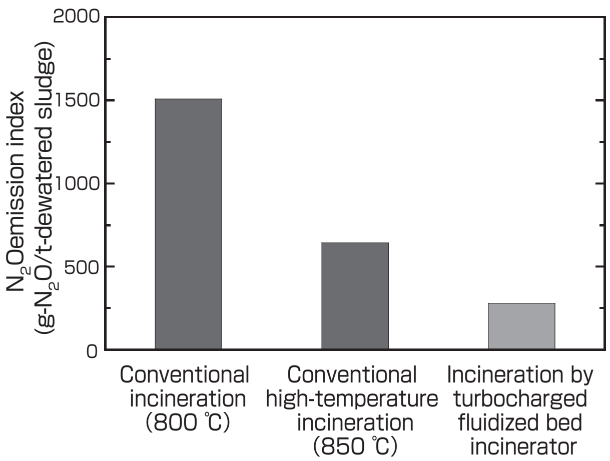

Fig. 9 Comparison of N_2O emissions[9]

The fundamental combustion experiments at AIST were carried out at over 0.6 MPa due to the limitation of the facility. Rearrangements were done to the facility for the demonstration experiment, combustion experiments were done at 0.2-0.3 MPa that was the same condition as the demonstration plant, and it was confirmed that the N_2O emission was dependent on temperature rather than operating pressure.[6] Also, to theoretically support the N_2O reduction effect, we calculated the freeboard temperature distribution using CHEMKIN, a software tool for solving complex chemical kinetics. As a result, as the pressure increased, the high-temperature region was produced in the lower part of the freeboard, and the same tendency as the demonstration plant was obtained.[9][10] The reason we were able to quickly clarify the cause of the N_2O reduction was because we were able to link the results of the basic research and the demonstration test.

Moreover, the emission of NO*x* was low similar to the basic research results at AIST, and we were able to half the amount compared to the conventional type. This was because, as mentioned earlier, the inhibition of NO*x* production by steam in the combustion gas and the NO reduction by char in the

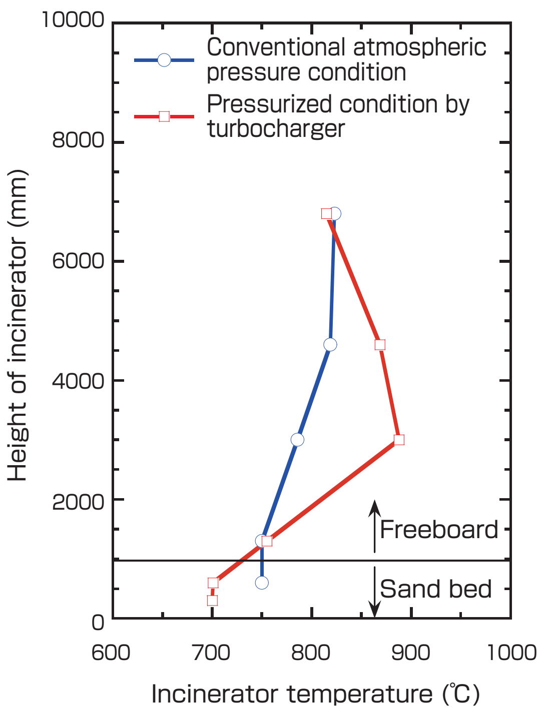

Fig. 10 Comparison of the temperature distribution in the fluidized bed incinerator[10]

fluidized bed were enhanced by pressurization.

In the completed system, the power consumption was reduced by about 40 %, use of supplementary fuel by about 10 %, NO*x* emissions by about 50 %, and N_2O emissions by about 50 %, compared to the conventional system. For the greenhouse gas reduction effect (by CO_2 equivalent), about 4,000 ton per year could be expected for one 100 t/d capacity plant that is the average scale in Japan. There are about 240 sewage sludge incinerators in Japan, and estimating that about half of them introduce the new type, the reduction of about 480 thousand ton/year can be expected. This is about 7 % of the total greenhouse gas emissions by the sewage treatment plants in Japan. From the above, it was demonstrated that the turbocharged fluidized bed incineration system was an innovative system that can achieve energy savings as well as low environmental impact.[2]

As a result of the PR activities after the completion of the NEDO project, the Bureau of Sewage, Tokyo Metropolitan Government took notice of this technology. As a final technological evaluation, a joint research with two private companies was started in 2008 for the long-term durability test. Long-time operation was conducted and continuous operation of a total of 2,000 hours was successfully achieved. The reliability and durability of the turbocharger were confirmed, this technology was employed in the Earth Plan 2010 that set the greenhouse gas reduction as its goal, and an order was received for the commercial plant at the end of FY 2010. This first plant has the sludge incineration capacity of 300 t/d, and it is one of the largest plants in Japan. It is about 60 times larger in size than the demonstration plant, but the scale-up method of the fluidized bed incinerator has been already established. In common scale up methods, the combustion load or the sludge feed rate per cross-sectional surface area of the incinerator is matched, and basically the incinerator size is increased only in the radial direction, and the gas velocity and residence time of the gas in the incinerator are the same even if the plant scale is increased. The temperature distribution along the height of the incinerator remains the same, the low environmental impact operation will be possible after scaling up, and no major trouble is expected in its operation.

4 Technological ripple effect

In the FY 2010, the first order was received for the commercial plant with 300 t/d scale from the Kasai Water Reclamation Center, Tokyo. It was scheduled to start operation by the end of FY 2013. Including the first unit, orders for five units were received as of present.[11][12]

1 Kasai Water Reclamation Center, Tokyo; 300 t/d scale
2 Asakawa Water Reclamation Center, Tokyo; 60 t/d scale
3 Shingashi Water Reclamation Center, Tokyo; 250 t/d scale
4 Sagamigawa Ugan Treatment Plant, Kanagawa Prefecture; 100 t/d scale
5 Aigawa Region Sewage Central Mizu Mirai Center, Osaka; 100 t/d scale

The first to start operation among the five units was the unit for Asakawa Water Reclamation Center, and it commenced operation at the end of January 2013, went through a test run period, and the opening ceremony was held on April 26 at the site. The related patent applications were submitted (currently 11), and income from the patent fee would be expected for AIST after the start of operation. As a national research institution, we believe we were able to contribute to society through this technology. Also, as mentioned earlier, this technology was born from the advantage of Tsukuba at which various research institutes are concentrated, and it is a good example that indicates a direction for the technological development that should be done at the Academic City.

In receiving the order for the first plant, the press release was conducted at PWRI,[13] and there was great response from newspapers.[14] This practical application was recognized in the academic society, and the technology won several awards including the SCEJ (Society of Chemical Engineers, Japan) Award for Outstanding Technological Development in 2012, SCEJ Award for Technology for Fluidized Bed Working Group in 2011, Encouragement Award for Papers, Society of Environmental Instrumentation Control and Automation in 2008, and Encouragement Award, Japan Institute of Energy in 2008.

There are about 240 sewage sludge incinerators in Japan, and it is projected that the plants will be actively updated in the future, and the number of orders is expected to increase. There are several new technologies proposed for the sewage sludge treatment process instead of simple burning,[15][16] but the technology described in this paper was the first to be put to practical use. AIST is preparing a quick technological support plan for emergencies such as troubles during the operation of the commercial unit.

5 Future prospects

Until now, we have conducted research specifically for sewage sludge. As mentioned earlier, sewage sludge is fuel with high water content, and this technology is expected to be applied to similar high water content fuel such as livestock excrement or alcoholic beverage lees. Moreover, it can be applied to overseas use such as in China and Korea where waste is currently buried but where incineration is expected to become mainstream in the future.

Looking at each component technology, the turbocharged fluidized bed incineration system that was established in this research is not new, but is a combination of existing equipment. In this research, we showed that there is potential that a new thing may be born from new ideas, and we hope to continue our study.

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Authors

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Completed the master’s course at the Department of Applied Chemistry, Faculty of Science and Engineering, Waseda University in March 1980. Joined the National Research Institute for Pollution and Resources, Agency of Industrial Science and Technology, Ministry of International Trade and Industry in April 1980. Was in charge of liquefaction of coal at the Sunshine Headquarter, Agency of Industrial Science and Technology in 1988. Senior Researcher, Research Institute of Energy Utilization, AIST in 2001; and Leader, Clean Gas Group, Energy Technology Research Institute, AIST from October 2005 to present. Since joining AIST, engaged mainly in the research of the combustion and gasification of coal, biomass and waste by fluidized bed. Obtained doctorate (Engineering) for the research of pressurized fluidized bed combustion in 2005. In this paper, was in charge of the laboratory-scale sewage sludge incineration experiment using the pressurized fluidized bed, and supported the development from the early stage of the project.

Takahiro MURAKAMI

Obtained the necessary credits but withdrew from the Department of Environment and Life Engineering, Graduate School of Engineering, Toyohashi University of Technology in March 2001. Became a faculty member of the Department of Ecology Engineering, Graduate School of Engineering, Toyohashi University of Technology in April 2001. Joined the Core Technology Research Department, Research Laboratory, Ishikawajima-Harima Heavy Industries Co., Ltd (current IHI Corporation) in October 2001; and appointed to the Thermal and Fluid Technology Department in April 2002. Joined as a Researcher, Clean Gas Group, Energy Technology Research Institute, AIST in April 2007; and Senior Researcher from October 2012 to present. Obtained doctorate (Engineering) in December 2001. Specialty is energy and environment field. In this paper, was in charge of the laboratory-scale sewage sludge incineration experiment using the pressurized fluidized bed, and the analyses of gas emission and operation results of the demonstration plant.

Akio KITAJIMA

Completed the doctor’s course at the Department of Mechanical Engineering, Graduate School of Science and Technology, Keio University in 2000. Doctor (Engineering). Joined the National Institute for Resources and Environment, Agency of Industrial Science and Technology, Ministry of International Trade and Industry in April 2000. Researcher, Research Institute of Energy Utilization, AIST in 2001; and Senior Researcher, Combustion Evaluation Group, Energy Technology Research Institute, AIST from October 2013 to present. Researcher of Public Invitation Proposal Project, New Energy and Industrial Technology Development Organization (NEDO) between 1998~2000. Industrial Science

and Technology Planner, Startup and Technology Affairs Division, Small and Medium Enterprise Agency, Ministry of Economy, Trade and Industry in 2011~2012. Engages in research for control of the combustion phenomenon in practical incinerators from the aspects of experimental and numerical analyses. In this paper, was in charge of the analysis of N_2O inhibition mechanism using detailed numerical calculation for chemical reaction in the gas combustion region inside the incinerator.

Discussions with Reviewers

1 Overall (Yasuo Hasegawa, AIST; Akira Kageyama, Research and Innovation Promotion Headquarters, AIST)

This is a comprehensive paper that explains the joint effort with other institutes and companies, for the design, development, evaluation, and demonstration testing of a new system to achieve energy savings and low N_2O emissions, looking at the sewage sludge incineration system that will soon need updating. We determined that the content is appropriate as a paper for *Synthesiology*.

I think it will be informative to the readers as the paper shows the way of conducting R&D where the technology generates value in society and is put to practical use.

Question and Comment 1 (Yasuo Hasegawa)

I think this is a good example where the private companies along with AIST and PWRI, which are research institutes located in Tsukuba but have different disciplines and are under different agencies/ministries, complemented each other's potentials and succeeded in the practical application of a technology.

I think targeting the City of Tokyo, a representative of local governments, is effective in promoting the introduction of the new system. Can you clarify the difficulty in introducing the new system to the local governments, and what the role of PWRI was? I think the demonstration research played an important role in the practical application, is that so?

Answer 1 (Yoshizo Suzuki and Takahiro Murakami)

PWRI that belonged to MLIT which controls the sewage works played a central role in starting the project, as they first explained the excellence of this technology to the local governments in Japan. Although the local governments showed quite an interest, they said that they would make decisions after seeing the stable operation of the first unit. With such a background, Bureau of Sewage, Tokyo Metropolitan Government showed great interest in this technology, and started joint research with the two private companies. This technology was taken up in the Earth Plan 2010 that proposed reduction of greenhouse gas, and that was a major step up. Tokyo Metropolitan Government plays a central role in the sewage treatment business, and the other local governments were closely watching what Tokyo would do. For the introduction of the actual unit, the performance evaluation by long-time continuous operation of the demonstration system was important. We were able to demonstrate that there was no problem in the performance or operation through the demonstration research, and that ultimately led to their decision.

Question and Comment 2 (Akira Kageyama)

This paper takes the core issues that the sewage sludge incineration facilities that were installed in the 1980s to 1990s are facing the need for updating, and that the current incinerator consumes a large amount of energy and produce relatively high concentration of nitrous oxide. Therefore, the development of a new sewage sludge incineration system with low energy consumption and low N_2O concentration was started.

AIST with the accumulation of elemental technologies for pressurized combustion, PWRI with the knowledge of evaluation/design technologies of sludge incinerator, and the related companies gathered. The point to note is that the parties worked to develop a new sludge incineration system while complementing each other, and obtained innovative results.

Answer 2 (Takahiro Murakami)

At the beginning of development of this system, we created a concept that placed importance on a system that can save energy. Therefore, we came up with the idea that we can eliminate the two fans with high power consumption by burning the sludge under pressurized conditions and by making combustion air by processing the high-temperature and high-pressure flue gas with a turbocharger. The N_2O reduction was positioned as secondary, or something to be looked at after the results of the combustion tests, but we were able to obtain good results where the emissions could be halved compared to the conventional high-temperature incineration.

Question and Comment 3 (Akira Kageyama)

In the development of the system using the turbocharger, was there any technological issues in the turbocharger itself? In this research, it is a victory of the creative use of information that enabled you to obtain the participation of companies that were manufacturers of both gas turbines and turbochargers. In conducting a true synthesiological research, I think the efforts of bringing out the creative use of information and the integration effect of multiple companies and institutions are important, not just the technological development in a narrow sense.

Answer 3 (Takahiro Murakami)

In introducing the turbocharger system, the technological hurdle was the durability of the turbocharger. The joint research for long-term durability tests was started with two private companies from FY 2008. Long-time operation was conducted, and we succeeded in continuous operation of over a total of 2,000 hours. We were able to clarify that there were no problems in the reliability and durability of the turbocharger, and this led to practical application.

The point of success was that among the gas turbine manufacturers that had strong linkage with AIST through various R&Ds, we were able to link up with those who sufficiently understood the basic concept of this R&D. We were able to quickly build collaborative relationship with the companies that had experience in manufacturing not only gas turbines but also turbochargers, in addition to the sewage sludge incineration plant manufacturers.