Advantageous effects of low air ratio combustion in an advanced stoker-type waste incinerator

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Abstract

Measures such as low air-ratio combustion and exhaust gas recirculation (EGR) have become the subject of a great deal of attention with a view to reducing the amount of environmental impact substances from the waste incineration process, and also to making the most effective use of energy. However, it has been understood that there would be considerable difficulty utilizing low air-ratio combustion in a conventional grate furnace. The application of high-temperature air combustion technology for enhancing sound combustibility could provide solutions to these problems and has been previously studied.

A practical test was conducted at a 105 ton per day capacity municipal solid waste stoker-type incineration plant. The test demonstrated that stable low air-ratio combustion operation is possible at a stoichiometry of 1.3 with EGR and high-temperature air combustion technology resulting in a 17% decrease in flue gas flow, an energy efficiency improvement of 10%, and a significant reduction of toxic product emission such as nitrogen oxides and dioxins when compared with a stoichiometry of 1.6 in the conventional process.

Keywords: municipal refuse incineration, combustion, pollutant, low air-ratio combustion, high temperature air combustion, NOx, dioxins.

1 Introduction

The demands on modern municipal solid waste (MSW) incineration plants in Japan are very much focused on minimizing toxic product emission, high-
energy efficiency and low construction and maintenance cost. Measures such as low air-ratio combustion is particularly promising solutions for the above issues, while a constellation of studies and developments has been conducted. Especially, utilizing low air-ratio combustion on the classic "stoker-type incinerator" furnace is eagerly anticipated. The stoker-type has a number of outstanding features, including no special pretreatment requirements for waste with heterogeneous and various properties such as crushing, long continuous availability, and its high share of the market which accounts for more than 80% (throughput base) of MSW incineration plants in Japan [1], and which is expected to play a major role in waste management. However, it has been understood that there would be considerable difficulty utilizing low air-ratio combustion on the stoker-type incinerator due to inevitable problems such as blow off, incomplete combustion or local heating caused by insufficient excess air used as the drying process of the heterolytic waste, or the furnace room temperature control. The application of high-temperature air combustion technology could provide solutions to these problems.

This development work is focused on the application of high-temperature air combustion technology [2] for resolving fundamental problems in combustion technology resulting from the versatility and heterogeneity of waste materials. In order to systematically investigate combustion characteristics of wastes, a 500 kilograms per hour pilot-scale plant has been constructed and run for more than 5000 hours using model wastes and actual municipal wastes. In addition, based on these results, a practical operational test was carried out at a 105ton capacity per day scale MSW incinerator in commercial operation. This paper will go through the process of the experimental study carried out with the pilot plant and describe the result of the practical operation test through implementing this high-temperature air combustion technology.

2 Advanced stoker-type incinerator with high-temperature air combustion technology

High-temperature air combustion technology is an effective combustion technology utilizing air preheated by heat recirculation from flue gas to above the autoignition temperatures of gaseous fuels, and holds great potential for realizing energy efficient and ecological combustion systems. The effectiveness of this advanced combustion technology for combustion performance; energy savings, CO₂ reduction, and reduced emission of nitrogen oxides, was recognized during an earlier phase of the research and development of industrial furnaces supported by the New Energy and Industrial Technology Development Organization (NEDO) as a national project.

The expected benefits of high-temperature air technology are the possibility of realizing low air-ratio combustion below a stoichiometric air ratio of 1.3 through superior combustion stabilization in the MSW incinerator while at the same time reducing the amount of substances that have environmental impact. The conceptual diagram for implementing the proposed system, “Advanced stoker-type incinerator” is shown in Fig.1, and that for the flame pattern in the
vicinity of the high-temperature air nozzles is shown in Fig.2. In practice, the mixture of high-temperature air and flue gas (this mixture is defined as “high temperature mixed-gas” in this paper) is injected at high velocity from opposite walls of the incinerator to form a stable stagnation space in the combustion initiation region above the fuel bed resulting in a luminous flame in this region. This stagnation space avoids fluctuations in or localized extinguishing of the flame, while at the same time heating the waste directly with the flame to promote pyrolysis.

![Figure 1: The conceptual diagram of the advanced stoker-type incinerator.](image)

![Figure 2: Flame stabilization image in the combustion initiation region.](image)

3 Pilot-scale plant study

3.1 Experimental facility and conditions

An experimental study was conducted on a pilot-scale plant prior to practical application. The pilot-scale test plant consisted of a stoker-type incinerator with a capacity of 500 kilograms of waste per hour and gas treatment systems shown as Fig.3. The dimensions of the incinerator were 1.6 m wide, 3.7 m long, and 6.8 m high. The combustion gas is led to a cooling tower to lower the gas temperature, then to a bag house to filter the fly ash, and finally to an induced draft fan for discharge from the stack. The high temperature mixed-gas consisted of a highly preheated air from a regenerative heat exchanger and de-dusted...
exhaust gas supplied to the incinerator. A sonic thermograph system was installed in this furnace, in order to find out the horizontal temperature distribution of an approximately 800mm section above the grate surface.

![Diagram of MSW incineration pilot-scale test plant](image)

**Figure 3:** MSW incineration pilot-scale test plant.

The experimental study was conducted changing the stoichiometric air ratio as a parameter. The conditions were as follows; (a) a stoichiometry of 1.7, (b) a stoichiometry of 1.3 by means of the conventional process without high temperature mixed-gas injection, and (c) a stoichiometry of 1.3 with high temperature mixed-gas injection as an advance process. Waste from business activities was used as sample material, with its moisture adjusted to the same level of MSW by adding water prior to discharging. The condition of high temperature mixed-gas aligned temperature was 873K and the O$_2$ concentration 12%. The flue gas was sampled from a sampling port in order to continuously analyze chemical composition such as O$_2$, CO and NOx.

### 3.2 Results and discussion

#### 3.2.1 Combustion stability

Measured changes with time in the concentration of the flue gas components generated with the conventional process with a stoichiometry of 1.7 (a) and 1.3 without high temperature mixed-gas injection (b) are shown in Fig. 4 and with a stoichiometry of 1.3 with high temperature mixed-gas injection (c) is shown in Fig. 5. Reduction of the excess air ratio caused large fluctuations in the concentrations of flue gas components in the conventional process, and particularly in the CO concentration as shown in fig. 4. In the case of (c), a significant improvement in combustibility was observed even in a low air-ratio due to high temperature mixed-gas injection, whereas a great number of instantaneous CO concentration peaks exceeding 200 mg/m$^3$ were shown in the case of (b). This is attributed to the improvement of stability in primary combustion achieved by the stagnant space as discussed in Chapter 2. Almost the same result was confirmed in the temperature conditions of high temperature mixed-gas injection subsequently lowered to 673K.
3.2.2 NOx concentration

The NOx concentration in a stoichiometry of 1.3 with high temperature mixed-gas injection showed almost half the value of conventional combustion. The reasons are considered to be as follows: the diminution in thermal NOx generation due to the promotion of a homogeneous broadening of combustion as shown in fig.6, which was prevented from the combustion partially and produced a diluted oxygen atmosphere. At the same time, the conversion ratio of Nitrogen fraction in the fuel to NOx is held to a low level by reducing the surplus air in the primary combustion chamber.
3.2.3 Dioxin concentration in exhaust gas
Dioxin emissions showed a value 0.76 ng-TEQ/Nm$^3$ at the incinerator outlet and 0.13 ng-TEQ/Nm$^3$ at the stack. This means that the dioxin emissions of small-scale incinerators can be substantially reduced. One factor is that high temperature mixed-gas injection seems to affect the reduced concentration of particulate incombustibles and the relative components in the incinerator.

4 Practical application test at a commercial plant
Based on the results described in the previous chapter, the advanced stoker-type incineration system that adopted high-temperature air combustion technology was applied to a commercial plant and a practical application test was conducted.

4.1 Experimental facility
The plant hosting the tests, “Numanohata Clean Center" in Tomakomai City, Japan [4] – is a steam producing stoker-type incineration plant with a capacity of 105 tonnes MSW per day – and was completed at the year 1999. The plant specifications are shown in Table 1, and a schematic diagram of the plant with the experimental facilities is shown in Figure 7. This plant consisted of a horizontal grate type incinerator [3], a waste heat boiler, a bag house, an induced draft fan and various other equipments originally. The incinerator is equipped with a water spray cooling system to prevent an extreme high temperature in the furnace. Each functional air is supplied to (1) the primary combustion chamber via under grate subdivided 4 separate air zone as a primary combustion air, (2) via the injection nozzle in the sidewalls as a cooling air and to (3) the secondary combustion chamber as a secondary combustion air for the conventional combustion in a normal air-ratio combustion.

Table 1: Specifications of the commercial plant.

| Plant                      | Numanohata Clean Center  
|----------------------------| Tomakomai City          |
| Furnace type               | JFE HYPER stoker-type incinerator |
| Capacity                   | 105 t/d × 2 lines     |
| Flue gas cooling           | Heat recovery boiler (2.8M Pa,300 °C) and cooling tower |
| Bag house                  | with lime and activated carbon supply |
| Heat utilization           | Steam turbine (2.6M Pa,295 °C) and generator (2000kW) |

In order to deal with the low air-ratio combustion test, the conventional plant was improved to an advanced type by the addition of an exhaust gas recirculation system, a high temperature mixed-gas generator and its injection system. In a low air-ratio combustion, (2') the exhaust gas filtered by the bag house is resupplied to the primary combustion chamber in place of cooling air and (4) the high temperature mixed-gas consisted of kerosene burner flue gas, dust filtered exhaust gas and fresh air is also injected above the fuel bed via the injection nozzle located beneath the nozzle for recirculated exhaust gas or cooling air supply.
4.2 Experimental conditions

The practical application test was carried out changing the stoichiometric air ratio as a parameter in a manner similar to the pilot-scale plant study. The experimental conditions were (a) Conventional combustion: with normal air-ratio combustion under a sustainable stable combustion and (b) Advanced combustion: with low air-ratio combustion in a stoichiometry of 1.3 using high temperature mixed-gas injection and EGR. The condition of high temperature mixed-gas aligned the temperature of 673K and the O2 concentration of 12% ascertained by the pilot-scale plant study. The concentrations of CO, NOx and O2 in the flue gas, the gas temperature in the primary chamber and at the furnace outlet, the flue gas flow rate and amount of evaporation of boiler were measured continuously. The dioxin concentration in the exhaust gas was measured at the outlet of the waste heat boiler.

4.3 Results and discussion

4.3.1 Flame phenomena in incinerator

There is different complexion on the flame in the primary combustion chamber between conventional and advanced combustion conditions as shown in Photo 1. During normal air ratio with the conventional combustion, the primary combustion chamber was covered with a diffuse flame entirely. On the other hand, during low air-ratio combustion with the advanced combustion, a stable luminous flame was observed below the position of high temperature mixed-gas injection, while above this area, brightness decreases to such an extent that the condition of the waste feed section can be confirmed visually. The phenomena in the advanced combustion is due to the agitation and homogenization of pyrolysis gas in the combustion initiation region caused by the injection of high temperature mixed-gas, and the uniform low oxygen concentration atmosphere
in the primary combustion area caused by EGR. In addition, these dilution gas supplying made it possible to eliminate the need for the furnace water spray whereas in the conventional combustion, it was necessary.

![Combustion flame in primary combustion chamber.](image)

**Photo 1:** Combustion flame in primary combustion chamber.

![Time histories of O2, CO and NOx in flue gas.](image)

**Figure 8:** Time histories of O2, CO and NOx in flue gas.

### 4.3.2 Changes in gas composition

Changes in the flue gas composition with time during conventional and advanced combustion are shown in Figure 8. The boiler outlet oxygen concentration in the exhaust gas during conventional combustion averaged 8.1% meaning a stoichiometry of approximately 1.6, but in contract, the average value with advanced combustion was lowered to 4.8% resulting in stable combustion was sustained at a stoichiometry of 1.3. The CO concentration averaged less than 10 mg/m³ and no conspicuous peaks were observed in this case, confirming that the CO concentration is held to the same low level as in conventional combustion. Consequently, the flue gas flow rate at the stack is 17% lower in advanced low air-ratio combustion than in conventional combustion when the total heat input basis is 43, 400MJ/h equally (operation with steam generation of 15 t/h in advanced combustion).
The NOx concentration showed an average value of 197 mg/m$^3$ with conventional combustion, whereas with advanced combustion, reduced by nearly one half to an average of 105 mg/m$^3$ even without furnace water spray.

As with the pilot-plant test described in the previous chapter, these results confirmed that promotion of uniform mild combustion in the main combustion region by utilizing high-temperature combustion technology is effective in reducing NOx generation at the commercial plant.

### 4.3.3 Waste heat recovery improvement

The effect of heat recovery improvement under advanced combustion is shown in Figure 9. For example, assuming the total heat input is 43,400 Mcal/h, as in the trial calculation of exhaust gas reduction, steam generation is approximately 10% greater in low air-ratio combustion than in conventional combustion. This is due to a reduction in heat carried out by the exhaust gas and improved combustion by promoting uniform/mixed combustion in the combustion chamber.

![Figure 9: Waste heat recovery gain by low air-ratio combustion.](image)

**Table 2:** DXNs concentrations in flue gas at boiler outlet.

<table>
<thead>
<tr>
<th>DXNs conc. (ng-TEQ/m$^3$N $_12%O_2$)</th>
<th>Conventional</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.71</td>
<td>0.43</td>
<td></td>
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### 4.3.4 Dioxin concentration in exhaust gas

The dioxin concentration in the exhaust gas at the waste heat boiler outlet is shown in Table 2. As a result of combustion improvement by injection of high temperature mixed-gas and EGR in the main combustion region, the dioxin concentration was reduced by approximately 40% in comparison with conventional combustion. This indicates that a stable flame is formed as a result of high temperature mixed-gas injection, even under a low air-ratio condition, and consequently, complete combustion is achieved. A very low dioxin concentration on the level of 0.001 ng-TEQ/m$^3$N was observed at the stack after the bag house with both conventional combustion and advanced combustion.
5 Conclusion

The practical operation test was performed at a commercial plant at the following results and demonstrated that it is possible to supply an advanced stoker-type waste incinerator with excellent operational stability and easy operating features under low air-ratio combustion condition, which also minimizes environmental loads and improves energy recovery by applying the high-temperature combustion technology.

(1) The test demonstrated that stable low air-ratio combustion operation is possible at a stoichiometric air ratio of 1.3 in a commercial-scale stoker-type incinerator using high-temperature air combustion technology such as injection of high temperature mixed-gas and EGR. Consequently a 17% decrease in flue gas flow in comparison with combustion.

(2) Improved heat recovery by low air-ratio combustion was also confirmed, as shown by a 10% increase in boiler steam generation in comparison with the conventional process.

(3) The NOx concentration of the flue gas can be reduced by nearly one half of the conventional process to 105 mg/m$^3$$_N$ on average by the achievement of stable low air-ratio combustion.

(4) The dioxin concentration of the flue gas at boiler exit was reduced by approximately 40% in comparison with the conventional process by the improvement of the combustibility in the primary combustion chamber.

Acknowledgements

A portion of this research was supported by the NEDO through the Energy Conservation Center Japan (ECCJ) as a national project.

The authors would like to express their appreciation to Tomakomai City and the staff of the plant at Numannahata Clean Center for their generous understanding and cooperation.

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