Development of New Waste Gasification and Melting Technology Using Advanced Shaft Furnace and Low NO_x Combustion

～Scale-up and Status～

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Abstract

NIPPON STEEL ENGINEERING CO., LTD. (NSE) has been conducting research and development work on its Advanced Shaft Furnace that consumes less coke than conventional shaft-furnace type gasification and melting technology called Direct Melting System (DMS). NSE has also been developing technology for low-NO_x combustion that increase the energy recovery rate. By reducing carbon dioxide emissions, the application of this Advanced Shaft Furnace design and combustion technology helps satisfy the recent public demand for eco-friendly Waste to Energy plants. The Advanced Shaft Furnace and low-NO_x combustion were used at a new Waste to Energy plant built for the Tobu Chita Environment Association, which serves two cities (Obu and Toyoake) and two towns (Higashiura and Agui). The Tobu Chita Clean Center (also known as “EcoRe”) commenced full operation in March 2019. Performance tests confirmed the ability of the Advanced Shaft Furnace to reliably melt various kinds of waste with lower coke consumption and without compromising its ability to produce high-quality, non-toxic slag and metal in the same way as a conventional shaft furnace. The test results also demonstrated that low-NO_x combustion reduces NOx emissions to below the regulatory requirement. NSE intends to continue its research and development of waste disposal processes and innovation in the equipment for waste treatment systems to facilitate recycling and achieving a circular economy.

1 Introduction

Conventional shaft-furnace type gasification and melting technology (DMS: Direct Melting System) used for the direct melting of municipal solid waste by means of high-temperature gasification and melting promote thermal decomposition and gasification of the waste together with stable melting by the formation of coke bed layer with burning coke at the bottom of the furnace. This enables a wide variety of different waste to be processed and the production of high-quality slag and metal suitable for recycling, while also enabling the downstream combustion chamber to achieve complete homogeneous combustion of the syngas discharged from the melting furnace. Meanwhile, growing concern about global environmental problems over recent years has led to require the waste management sector to further reduce its CO_2 emissions to help prevent global warming. Nippon Steel Engineering (NSE) has been addressing this issue by reducing coke consumption, which has the most direct influence on CO_2 emissions.

In order to reduce coke consumption, NSE has developed multi-tuyere system and combustibles injection system via tuyeres such as plastics, combustible dust, and fuel gas[1), 2), 3)]. While these measures have been put into practice and have succeeded in reducing coke usage per ton of waste from around 100 kg to around 40 kg, further reductions in coke consumption are required from the market for reducing CO_2 emissions from fossil fuel. In response, NSE has developed an Advanced Shaft Furnace that is designed to recover as much energy as possible from waste, with a significant reduction in the coke consumption. This Advanced Shaft Furnace has achieved higher reaction efficiency of drying and thermal decomposition of waste with an improved blower mechanism at the upper tuyeres of the conventional shaft furnace[4), 5), 6), 7)].

NSE has established technology for Advanced Shaft Furnaces through trial runs at a 20 t/day pilot plant and at a 65 t/day demonstration plant to verify the reduction of coke consumption and plant reliability. A further scaling-up theory has been developed through the trial runs at the 65 t/day-scaled demonstration plant, resulting in the completion of the Tobu Chita Clean Center, a new 100 t/day Advanced Shaft Furnace.

In recent years, Waste-to-Energy (WtE) plants have come to be recognized as more than just a hygienic means for detoxifying and reducing the volume of waste material, and rather as an autonomous and decentralized form of energy supply. The plan for waste disposal and processing facilities agreed to at a meeting of Japan's cabinet in June 2018 stated that WtE plants, which were installed during the period of the plan (which runs from FY2018 to FY2022), aim to increase the average electricity generation efficiency from its current level of 19% to 21%[8)]. Against this background, WtE plant suppliers need to improve power generation efficiency in order to contribute to the low-carbon society (circular economy), through technical innovation in processes and equipment without compromising the safety and reliability of waste processing. NSE has been addressing the issue by pursuing the development of techniques for low-NO_x combustion that should also improve power generation efficiency by reducing the quantity of combustion air as well as NO_x emissions to minimize the amount of heat escaping the system via flue gas at boiler outlet.

This article describes the operation of the Tobu Chita Clean Center, which utilizes an Advanced Shaft Furnace together with techniques for low-NO_x combustion.

2 Plant Overview

The Tobu Chita Clean Center (also called "EcoRe") was constructed by the Tobu Chita Environment Association, which serves two cities (Obu and Toyoake) and two towns (Higashiura and Agui), to process municipal solid waste. The completed center commenced operation in March 2019, replacing the existing plant (see Figure 1). The center employs an Advanced Shaft Furnace with state-of-the-art technology and makes use of the advantages of shaft-furnace type gasification and melting technology called a Direct Melting System (DMS), which [1] processes many kinds of waste with reliable and stable melting and gasification, [2] minimizes the final amount of landfill, and [3] reduces CO_2 emissions. The plant also features low-NO_x combustion techniques that minimize the formation of NO_x in the combustion process, and improve the electricity generation efficiency by reducing surplus combustion air.

Figure 1 Facility appearance

Table 1 lists the main specifications. The plant is an Advanced Shaft Furnace with a capacity of 200 t/day (2 × 100 t/day furnaces). To improve generation efficiency, this plant employs selective noncatalytic reduction (SNCR), high-temperature/high-pressure boilers, and an extraction-condensing turbine system.

Figure 2 shows a process flow. The moisture content of the waste supplied to the gasification and melting furnace evaporates, and after drying, the combustibles are thermally decomposed. Charged coke forms a high-temperature coke bed at the bottom of the furnace and melts incombustibles that remain after thermal decomposition at the upper part of the furnace. The molten materials are discharged from a tap hole at the bottom of the furnace and quenched by jet water. Generated slag and metal are completely recycled after being magnetically separated. The syngas that forms in the furnace is supplied to the downstream combustion chamber where it is mixed with combustion air and burned completely. The combustion chamber is designed to generate rotational flow so as to achieve uniform burning by circulating combustion. A key feature of this shaft furnace gasification and melting system is that the combustion chamber and the gasification and melting furnace are separate, with independent control of each, achieving both full gasification and melting and full combustion. The flue gas first passes through a boiler to recover heat and is then rapidly cooled in a gas cooler to prevent dioxin reformation and to improve the reaction efficiency of downstream dry dechlorination. The flue gas then passes through a bag filter before being discharged via an induced-draft fan from the stack. The steam produced in the boiler is supplied to a steam turbine-generator to generate electric power that is used on site, with the excess being sold to the grid.

Table 1 Center specifications and equipment

Name	Tobu Chita Clean Center (“EcoRe”)
Construction	April 16, 2015 to March 8, 2019
Waste processed	Combustible waste, crushed combustible waste, dewatered sludge
Capacity	200 t/day (2 × 100 t/day furnaces)
Furnace type	Shaft gasification and melting furnace
Waste handling equipment	Pit and crane system
Combustion gas cooling	Boiler for all waste heat (3.9 MPa × 400 °C)
Flue gas treatment	Bag filter system, SNCR & dry dehydrochlorination and sulphur oxide removal
Excess heat utilization	Extraction-condensing turbine (4,450 kW), hot water supply

3 Technologies Used

3.1 Low-carbon shaft furnace

3.1.1 Overview

Figure 3 shows a diagram of the Advanced Shaft Furnace. The design of the Advanced Shaft Furnace aims to achieve uniform blowing from the bottom of the shaft by improving the blower mechanism for the shaft section where waste drying and thermal decomposition occurs in a conventional shaft-furnace type gasification and melting furnace (Air [1]). This improves heat exchange efficiency between the waste packed in the furnace and the generated syngas more uniformly through the shaft. In a conventional shaft furnace, passing the air from the tuyeres (Air [1]) uniformly to the horizontal center of the furnace could be problematic, with the result that the waste descending to the melting zone at the bottom of the furnace would still contain moisture, requiring increased coke consumption in order to remove this moisture. In contrast, the Advanced Shaft Furnace, uniform air blowing from the entire base of the shaft (Air [2]) significantly improves the efficiency of heat transfer from the syngas to the waste.

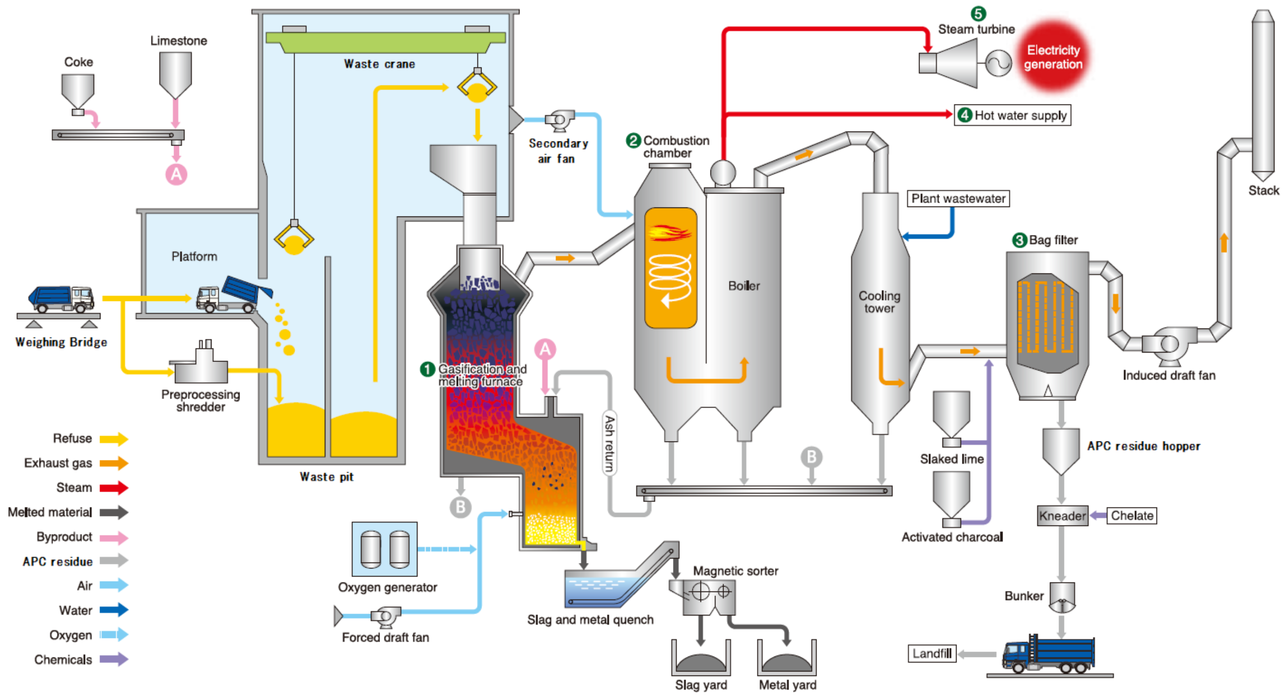

Figure 2 Process flow

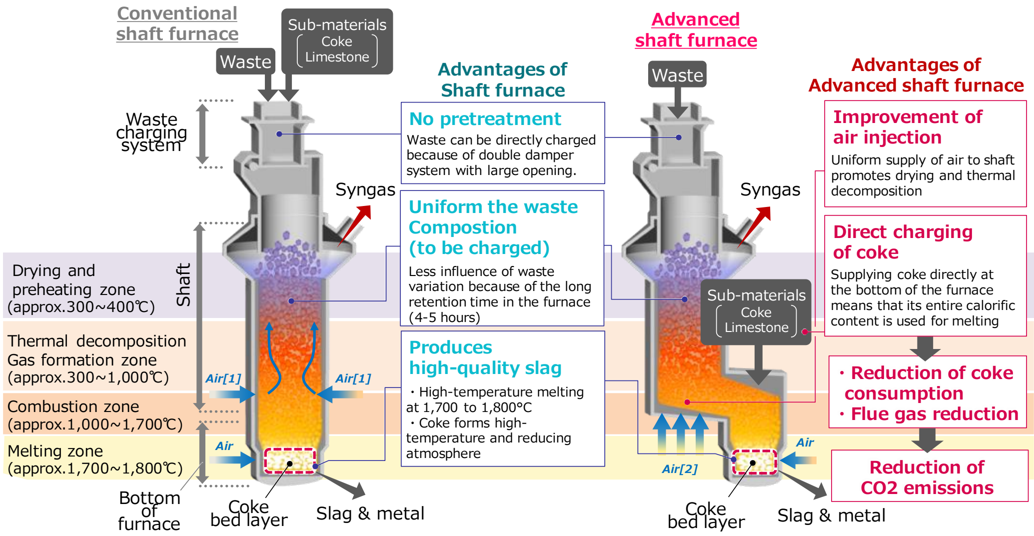

Figure 3 Low-carbon waste melting plant (comparison to conventional plant)

Depending on the carbonizing ratio resulting from the uniformed air blowing, the air volume and the rate for the descending carbonized waste at the bottom of the furnace can be optimized. This means that the waste descending to the melting zone at the bottom of the furnace has been fully carbonized and does not require any additional coke consumption for moisture evaporation. Consequently, only as much coke as is needed to melt the ash is required at the bottom of the furnace. The ash content of the waste is completely melted at the bottom of the furnace, producing the same high-quality slag and metal as a conventional shaft furnace. The Advanced Shaft Furnace succeeds in significantly reducing coke consumption while still maintaining the same capabilities as a conventional shaft furnace for accepting a wide variety of different forms of waste without any pre-treatment such as crushing, sorting, or other preliminary processing, also producing slag and metal suitable for recycling.

Along with lower CO_2 emissions, the changes to the blowing process in the Advanced Shaft Furnace also make the plant more compact with fewer pieces of equipment. In addition as another advantage, particulates are less likely to be carried from the gasifier to downstream processes, as the sub-materials (coke and limestone) are charged from the bottom of the furnace rather than the top of the shaft part.

3.1.2 Development of Advanced Shaft Furnace

[1] 20 t/day pilot plant

Trial runs on the pilot plant were conducted for a total of 101 days spread over 15 test runs, including a large amount of fundamental experimentation. As shown in Figure 4, operational testing achieved coke consumption of 14 kg/t of waste during continuous operation (compared to approximately 40 kg/t for a conventional shaft furnace). The plant was also successfully operated for 30 days continuously without interruption to demonstrate its capability for long-term reliable operation.

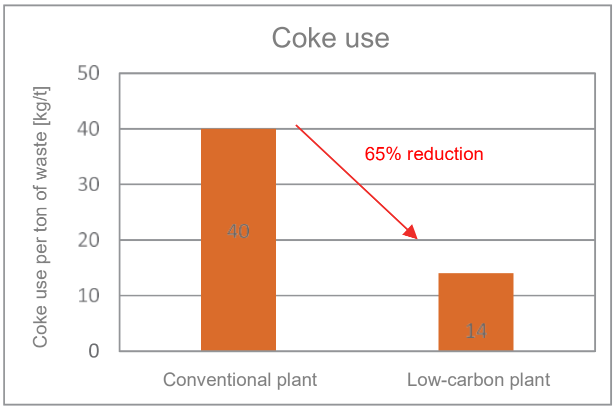

Figure 4 Reduction in coke use

[2] Demonstration trial on 65 t/day plant

To extend the achievement at the 20 t/day pilot plant to full-scale deployment, a conventional shaft furnace with a capacity of 65 t/day was converted to an Advanced Shaft Furnace and a demonstration trial commenced in April 2012. The feedstock to be processed was municipal solid waste made up of a mix of combustible waste with incombustible waste discharged through household separation. As this waste to be processed had a higher ash content and lower calorific value than the waste used in the pilot plant, the coke consumption target of this new plant was set to be 20 kg/t. This value was 1/3 of that of the previous plant with a conventional shaft furnace (60 kg/t). The demonstration trial operated on a total of 489 days spread over 8 test runs, finishing in March 2014. During this time, 30,791 tons of waste was processed. The upgraded plant has continued to operate successfully since the end of the demonstration trial (as of August 2019).

The first trial run was conducted for determining the basic characteristics of the Advanced Shaft Furnace with a varying range of operating conditions. This provided a basis for tuning the control system and establishing base operating conditions. The following trial run was conducted to confirm long-term continuous operation and the reduction in coke consumption using the basic operating conditions found in the previous runs. As it was anticipated that the operating situation in the gasifier would be varied a lot, countermeasures for these variations of operating situation were prepared beforehand and their effectiveness was assessed. The next trial run improved operating conditions and actions aimed at further reducing coke consumption. Between each trial run, the plant was opened for inspection to check the inner conditions. Further modification has been done using operation evaluation and analyses.

As can be seen in Table 2, the optimizations made to the operating conditions over each trial run successfully reduced coke consumption down to around 15 kg/t during normal operation. The trials succeeded in maintaining continuous operation for 44 and 94 days at a time and in achieving the goal of reducing coke consumption of below 20 kg/t.

Table 2 Results of demonstration plant test

Test duration	Days	44	94
Amount of waste processed	t/d	71	70
Coke use per ton of waste	kg/t	14.8	15.1

Data collection continued after the demonstration trial and work was completed on acquiring design data for scaling up to larger plant capacities, applying to the 100 t/day Tobu Chita Clean Center project.

3.2 Low NO_x Combustion

At Tobu Chita Clean Center, techniques for low-NO_x combustion were adopted for the combustion chamber located at the downstream section of the Advanced Shaft Furnace to minimize NO_x emissions without using flue gas recirculation.

Two-stage combustion and combustion with a low excess air ratio are well known as the primary measures for NO_x reduction. For two-stage combustion, in the first stage, combustion air with an excess ratio of about 0.8 is injected in order to decompose the NO, HCN, and NH_3 formed from nitrogen in the fuel with high temperature and long retention time. Then, in the second stage, the additional combustion air is injected into the downstream stage to achieve complete combustion. The proportion of nitrogen in the fuel that is converted into NO_x is called the conversion ratio and is higher for higher oxygen concentrations. Combustion with a low excess air ratio minimizes the NO_x conversion ratio by reducing the residual oxygen concentration in the zone where combustion is completed. These two measures (two-stage combustion and combustion with a low excess air ratio) are used in an independent combustion chamber to achieve low NO_x emissions.

As a low excess air ratio reduces the amount of combustion air to be supplied, it diminishes the degree of gas-air mixing and makes it more likely that unburned gas will remain. For this reason, in general, flue gas recirculation is applied for combustion with a low excess air ratio in order to maintain mixing performance in the combustion zone. However, flue gas recirculation imposes additional capital and maintenance costs due to the piping and other equipment required. In contrast, the shaft furnace gasification and melting system of NSE can maintain a high level of mixing with turbulence combustion in the combustion chamber, taking advantage of this to simplify the plant design by achieving low-NO_x combustion without flue gas recirculation.

Figure 5 shows an overview of low-NO_x combustion. In the previous combustion conditions, the primary air is injected from the main burner port and its lower part. Then the secondary air is injected into the turbulence flow. The syngas mixed with primary air forms a flame, circulating as it burns. The atmosphere in the combustion chamber is oxidizing with an excess air ratio of 1.0 or higher. In this case, the amount of NO_x generation is between 100 and 140 ppm.

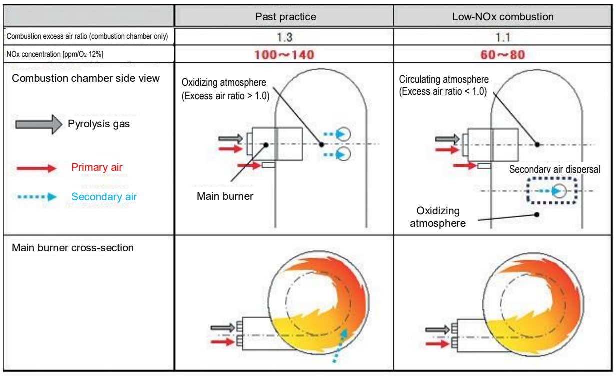

Figure 5 Overview of low NO_x combustion (comparison with past practice)

In the low-NO_x combustion applied in this research, the secondary air is supplied spread across the central part of the combustion chamber, keeping the primary excess air ratio below 1.0. This results in a long residence time with the high-temperature reducing atmosphere in the upper part of the combustion chamber where NO, HCN, and NH_3 breaks down into N_2. The remaining unburned gas is then fully combusted with the secondary air supplied to the central part of the combustion chamber. The secondary air using combustion with a low excess air ratio is able to limit NO_x formation to 60 to 80 ppm solely by combustion control without flue gas recirculation[9), 10)].

4 Operation at 100 t/day Plant

4.1 Performance test for plant handover

The Tobu Chita Clean Center was completed in March 2019 following the completion of a hot commissioning period that ran from October 2018 to February 2019. Table 3 lists the plant performance during a three-day handover test (from February 15 to 17, 2019) in terms of the amount of waste processed, coke consumption, and various emission measurements. Following tuning of the control systems and operating conditions during the hot commissioning period, both No.1 and No.2 lines achieved their design performance. The operating plant achieved coke consumption of approximately 20 kg/t, roughly half the previous level.

Table 3 Performance test results

	Units	Furnace 1	Furnace 2	Requirement
Amount of waste processed	t/d	106	106	≧100
Coke use per ton of waste	kg/t	21.3	20.3	-
Particulates	g/m^{3}N	<0.0007	0.0008	≦0.02
Hydrogen chloride	ppm	18	22	≦50
Sulfur oxides	ppm	4.0	4.1	≦50
Nitrogen oxides	ppm	31	42	≦70
Carbon monoxide (4h average)	ppm	4.4	1.9	≦30
Dioxins	ng-TEQ/m^{3}N	0.0018	0.0026	≦0.1

The flue gas emissions were significantly low against the limited values, indicating that the combustion measures applied in this research achieve both low-NO_x combustion and complete combustion at high temperature, minimizing dioxin formation. These results demonstrate that the Advanced Shaft Furnace was successfully scaled up to a 100 t/day plant.

4.2 Slag quality using Advanced Shaft Furnace

Tables 4 and 5 list the results of a JIS leaching test and JIS acid extractable content test on the molten slag during the performance test at plant handover. Both sets of results satisfied the requirements, demonstrating that melting and slag formation in the Advanced Shaft Furnace are occurring as they should despite only consuming 20 kg/t of coke, and that the furnace generates the same slag quality (in terms of safety and stability) as a conventional shaft furnace.

Table 4 Results of slag leaching test (JIS K0058-1)

Element	Unit	Amount leached	Requirement
Cadmium	mg/L	<0.001	≦0.01
Lead	mg/L	<0.005	≦0.01
Hexavalent chromium	mg/L	<0.01	≦0.05
Arsenic	mg/L	<0.005	≦0.01
Total mercury	mg/L	<0.0005	≦0.0005
Selenium	mg/L	<0.002	≦0.01
Fluorine	mg/L	<0.1	≦0.8
Boron	mg/L	<0.02	≦1.0

Table 5 Acid extractable content (JIS K0058-2)

Element	Unit	Quantity	Requirement
Cadmium	mg/kg	<1.0	≦150
Lead	mg/kg	5	≦150
Hexavalent chromium	mg/kg	<1.0	≦250
Arsenic	mg/kg	<1.0	≦150
Total mercury	mg/kg	<0.05	≦15
Selenium	mg/kg	<1.0	≦150
Fluorine	mg/kg	180	≦4,000
Boron	mg/kg	130	≦4,000

4.3 Low-carbon shaft furnace: Final landfill minimization using Advanced Shaft Furnace

Shaft-furnace type gasification and melting technology (DMS) sometimes employs a cyclone system in order to separate combustible dust from the syngas and reduce the Air Pollution Control (APC) residue. APC residue, which is the final landfill amount from DMS, with and without a cyclone system is 30 kg/t and 40 kg/t, respectively. The Advanced Shaft Furnace doesn't require this cyclone system as this furnace minimizes the transfer of particulates to downstream processes because of the direct charging of sub-material to the bottom of the furnace. Furthermore, improvements to the recovery of fly ash produced at the combustion chamber and boiler succeeded in roughly halving the amount of APC residue produced compared to a conventional shaft furnace without a cyclone system (see Figure 6). This leads the Advanced Shaft Furnace to reduce the final landfill amount dramatically compared with the conventional system.

4.4 CO_2 emission reduction using Advanced Shaft Furnace

In recent years, from the viewpoint of avoiding the global warning, further reductions in CO_2 emissions are required. The Advanced Shaft Furnace has addressed this issue by reducing coke consumption. As a result, the new plant with this Advanced Shaft Furnace succeeded in roughly halving its CO_2 emissions relative to a conventional shaft furnace with a similar waste processing capacity (200 t/day/plant) (see Figure 7). The

CO_2 emissions were calculated in accordance with the calculation methods and emission factors for the calculation, reporting, and disclosure system of Japan's Ministry of the Environment that are listed on its website.

4.5 Low-NO_x combustion: NO_x and CO concentration

Figure 8 shows the trend for the concentrations of NO_x and CO at the plant stack and the excess air ratio across the entire process. The graph also includes estimated NO_x formation (concentration). This NO_x concentration is estimated using and a proprietary correlation formula obtained by the measured concentration at the outlet of combustion chamber and operation parameters. During this test period, the mean excess air ratio was 1.47, mean NO_x formation was 56 ppm, mean NO_x at the plant stack after NO_x removal in the combustion chamber (SNCR) was 33 ppm, and mean CO concentration at the plant stack was 5.3 ppm. This indicates that the low-NO_x combustion succeeded in keeping the concentration of NO_x formed in the process to very low levels without flue gas recirculation, stably keeping the emissions limit value of 70 ppm. The CO concentration is also significantly lower than the limit value, indicating stable combustion conditions. The combustion with low excess air ratio achieved more than 10% reduction of the excess air compared to the values of 1.6 or more of the conventional plants. Along with reducing the NO_x generation, this also helps to cut power consumption by reducing the quantity of flue gas, as explained below.

4.6 Power consumption

Changing the air blowing process used in conventional shaft furnaces, the Advanced Shaft Furnace allowed the plant to be compact and reduced the quantity of equipment such as fans and Pressure Swing Adsorption (PSA) systems. This cut plant power consumption, as did the optimization of equipment control.

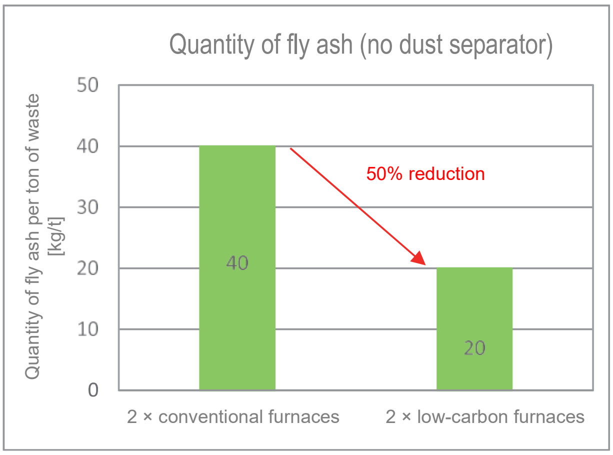

Figure 6 Comparison of gathered fly ash

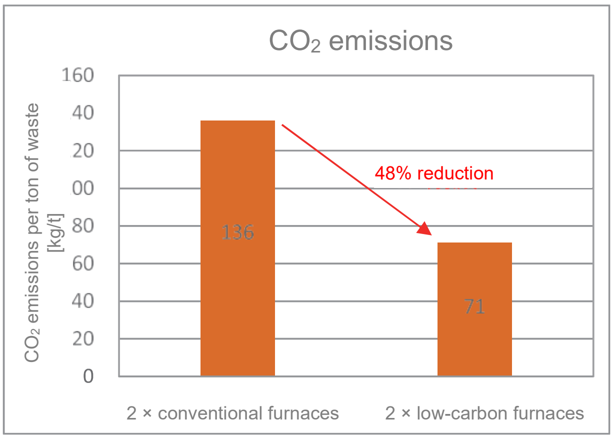

Figure 7 Comparison of CO_2 emissions

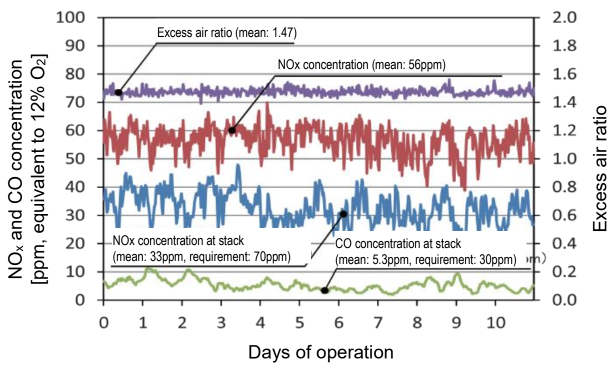

Figure 8 Trend graph of NO_x and CO concentration and excess air ratio

The power consumption of the Advanced Shaft Furnace is 150 kWh/t, a reduction of around 17% from the 180 to 200 kWh/t of a conventional shaft furnace (see Figure 9).

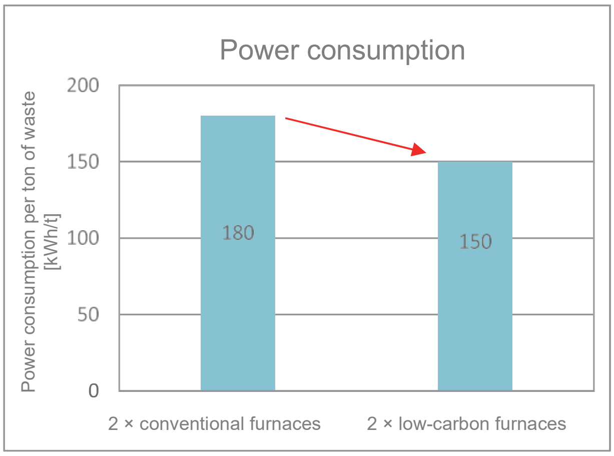

Figure 9 Comparison of power consumption

4.7 Operational performance

The plant has operated reliably since its completion in March 2019. Table 6 lists its performance over the months after completion. The waste throughput, coke consumption, power consumption, and APC residue were 95 - 100 t/day, 20 kg/t, 150 kWh/t, and 20 kg/t respectively. These results indicate that the plant with Advanced Shaft Furnace has been operating stably and reliably.

Table 6 Plant performance over time

	Unit		Mar.	Apr.	May	Jun.
Amount of waste processed	t/d	Furnace 1	98.3	98.8	96.9	95.2
		Furnace 2	97.5	99.0	98.9	95.2
Coke use per ton of waste	kg/t	Furnace 1	22.4	20.7	23.0	21.3
		Furnace 2	21.3	20.9	20.2	21.3
Power consumption	kWh/t	-	148.4	147.1	154.0	155.8
Fly ash production	kg/t	-	18.8	23.0	19.2	20.2

5 Conclusion

This paper has described how Nippon Steel Engineering's latest technologies for Advanced Shaft Furnaces and low-NO_x combustion are applied at the Tobu Chita Clean Center. The 100 t/day Advanced Shaft Furnace kept the advantages of the conventional shaft furnace such as waste flexibility, stable operation, and the production of high-quality slag with the significant reduction of coke consumption. The adoption of low-NO_x combustion also succeeded in reducing NO_x formation to very low levels without flue gas recirculation. Nippon Steel Engineering intends to contribute to the creation of a circular economy and low-carbon society by continuing to pursue innovation in process and mechanical technologies for WtE technologies.

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