JFE TECHNICAL REPORT
No. 19 (Mar. 2014)

Reduction of Coke Consumption in High-Temperature Gasifying and Direct Melting System†

UCHIYAMA Takeshi[*1] OKUYAMA Keiichi[*2] AKIYAMA Hajime[*3]

Abstract:

JFE Engineering has delivered waste to energy plants which use its unique high temperature gasifying and direct melting technology. These plants are able to treat and gasify various kinds of wastes and are capable of melting the ash through the usage of coke. In order to increase the environmental compatibility, JFE Engineering has developed various methods to reduce the consumption of coke. The possibility of using rice husk briquettes, wood briquette charcoal and natural gas as an alternative to coke had been investigated in commercial plants. It was found that rice husk briquettes can be utilized in substitution of coke and the usage reduction ratio exceeded 50%. Despite of the high temperature conditions in the furnace, the rice husk briquettes, which have volatile matter for ash melting, are able to reach the bottom of the furnace. It was also found that wood briquette charcoal can be a substitute for all coke. Additionally, the combined usage of rice husk briquettes and wood briquette charcoal can also substitute the coke entirely. Moreover, verification test on natural gas injection from main tuyeres at the bottom of the furnace was successfully carried out for about a month. Results showed that the coke consumption can be reduced by 60% through the usage of natural gas.

1. Introduction

The high-temperature gasifying and direct melting furnace simultaneously gasifies wastes and melts the ash using coke, and is capable of treating diverse types of waste, beginning with municipal solid waste (MSW) and also including industrial waste, incineration ash, excavated landfill waste, asbestos, etc. JFE Engineering has supplied 10 waste treatment plants employing this unique technology since construction of the first unit was completed in 2003[1)]. In response to heightened social demand for reduction of CO_2 emissions in recent years, the company actively studied methods of reducing CO_2 emissions by reducing coke consumption[2)]. As part of the previous research, tests were conducted at an actual waste treatment plant to reduce the consumption of conventional fossil fuel-derived coke (hereinafter, conventional coke) by using biomass-derived solid fuel. It was possible to reduce consumption of conventional coke by more than 50%[2)] in a test using a Bio-coke (highly densified biomass briquette) developed by Associate Professor Tamio Ida, Kinki University[3)]. Because Bio-coke is produced by molding various types of biomass under high pressure at torrefaction temperature, it has the distinctive feature of retaining the volatile matter of the biomass while also possessing high strength. JFE Engineering carried out tests using rice husk briquettes, which have a similarly high content of volatile matter, and demonstrated that use of conventional coke could be effectively reduced[2)].

In the present research, tests were carried out at an actual waste treatment plant with the aim of determining the limits of conventional coke reduction by using rice husk briquettes, which are economically attractive, and wood briquette charcoal, which is readily available in the market. Favorable results were obtained. In particu-

† Originally published in *JFE GIHO* No. 32 (Aug. 2013), p. 67–73

*1 General Manager,
Research Center of Engineering Innovation,
JFE Engineering

*2 Senior Researcher,
Research Center of Engineering Innovation,
JFE Engineering

*3 Deputy General Manager,
Environmental Solutions Sector,
JFE Engineering

lar, these tests confirmed that it is possible to replace 100% of conventional coke with biomass solid fuel, in other words, to operate without using conventional coke, by using wood briquette charcoal or a combination of this material and rice husk briquettes.

On the other hand, a method in which a high hydrogen-content fuel gas such as natural gas, is injected from the main tuyere as a substitute for coke is considered effective for reducing coke consumption, i.e., for reducing CO_2 emissions. This method has already been applied successfully in commercial blast furnace operation.

Expanding the range of fuels which can be substituted for conventional coke increases the flexibility of the high-temperature gasifying and direct melting furnace, and enables more economical operation by selecting and using the fuels which are least expensive in each region.

2. Outline of High-Temperature Gasfying and Direct Melting Furnace

Figure 1 shows a sectional view of the high-temperature gasifying and direct melting furnace. Waste, coke, and limestone are charged from the top of the furnace. In the upper part of the furnace, moisture is vaporized and the volatile matter is pyrolyzed. The fixed carbon and ash in the waste are preheated as they descend through the melting furnace with the charged coke and limestone, and reach the furnace bottom. A coke bed is formed in the furnace bottom, and the coke and fixed carbon are burned by oxygen-enriched air supplied from the main tuyere. The heat of the combustion process melts the ash, which is then discharged continuously from the slag hole as molten slag. Combustible gas is generated in the furnace from the top through the waste layer. Perfect combustion of this gas is performed in the secondary combustion chamber in the latter stage of the melting furnace. The heat of this perfectly-combusted gas is recovered by a boiler, and the gas is then sent to the flue gas treatment system.

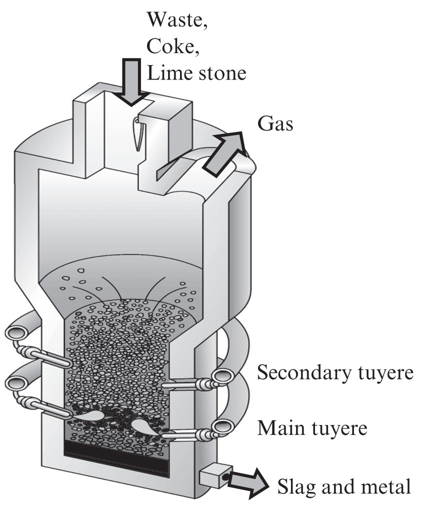

Fig. 1 Schematic configuration of high temperature gasifying and direct melting furnace

3. Test Methods and Results

3.1 Properties of Biomass Solid Fuel

3.1.1 Appearance and analysis values

Rice husk briquettes are a commercial product that is produced by extrusion molding of rice husks, which are an agricultural waste, with a rice husk briquette machine, and can be obtained comparatively easily and cheaply in rice-growing countries. The briquettes are cylindrical in shape, with a diameter of 53 mm and length of approximately 80 mm, and have a hole 15 mm in diameter in the axial center. The appearance of a briquette is shown in **Photo 1**(a).

Wood briquette charcoal is also a commercial prod-

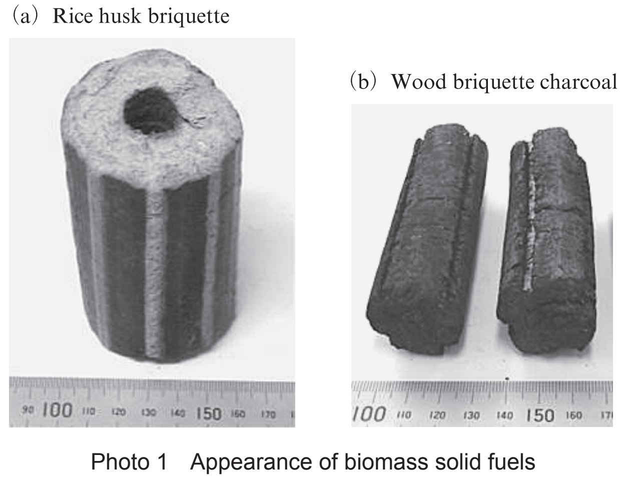

Photo 1 Appearance of biomass solid fuels

Table 1 Properties of biomass solid fuels

		Rice husk briquette	Wood briquette charcoal	Coke
Water	(mass%)	6.5	5.9	5.0
Ash	(mass%-dry)	16.0	6.2	12.6
Volatile matter	(mass%-dry)	67.1	5.9	1.6
Fixed carbon	(mass%-dry)	16.9	87.9	85.8
Lower calorific value	(MJ/kg)	14.23	30.09	29.26

uct, and is produced by extrusion molding of wood waste, followed by carbonization at high temperature. It is widely used as an alternative to expensive high-grade natural wood charcoal. The test materials used in the present research were cylindrical with a diameter of 30 mm and lengths of 30–100 mm. Typical wood briquettes are shown in Photo 1(b).

The results of analysis of the properties of rice husk briquettes and wood briquette charcoal are shown in **Table 1** in comparison with conventional coke. In comparison with conventional coke, rice husk briquettes have a lower content of fixed carbon and a larger content of volatile matter because the production process does not include carbonization, which is accompanied by release of the volatile component. Thus, effective utilization of the heating value possessed by the biomass solid fuel as a heat source in the furnace is expected.

In contrast, in wood briquette charcoal, substantially all of the volatile matter of the biomass is lost as a result of carbonization treatment. The content of fixed carbon is similar to that of conventional coke. Because the ash content of wood briquette charcoal is lower than that of conventional coke, its heating value is somewhat higher.

3.1.2 Strength test

The strength of the rice husk briquettes and wood briquette charcoal was evaluated by the test method which is used to measure coke strength. The measurement results are shown in **Table 2**. The test of the drum index DI_{15}^{30} follows JIS K 2151 (Coke—Testing Methods, JIS: Japanese Industrial Standards). In this method, the test material is charged into the prescribed drum, which is then rotated 30 times at the specified speed, and the weight ratio of the test material remaining on a 15 mm screen (15 mm oversize) is obtained. With the rice husk briquettes, in addition to measuring the test material in the as-received condition, the strength of the material was also measured after carbonization at 950°C for 18 hours as an index of strength after losing its volatile matter in the furnace.

Coke strength after reaction with CO_2, CSR (+9.5 mm), is obtained by reacting a carbon sample having a graded size of 20 mm with CO_2 at 1 100°C for 2 hours, charging the sample into an I-type drum at room temperature, rotating the drum 600 times at the speed of 20 rotations per minute, and calculating the weight ratio of 9.5 mm oversize. Here, in order to grade the rice husk briquette material under the same conditions as the carbonized wood briquette charcoal, the rice husk material was carbonized at 950°C for 18 hours before grading.

Table 2 Strength of biomass solid fuels

			Rice husk briquette	Wood briquette charcoal
Drum index	DI_{15}^{30} (%)	As received	96.8	60.5
		After pyrolysis	13.0*	—
Post-CO_2 reaction strength	CSR (+9.5 mm) (%)		0.0*	14.1

*Measured after pyrolysis (950°C, 18 h)

From Table 2, it can be understood that the drum index of the rice husk briquettes is high before carbonizing, but decreases greatly after carbonizing. Furthermore, the CSR value of the rice husk material was zero. This suggests that rice husk briquettes which have lost their volatile component cannot be used as a substitute for coke in the coke bed which is formed in the furnace bottom to maintain good descent of the slag. Hence, the expected effect of the rice husk briquettes is release of heat which contributes to ash melting during the period until the volatile component is lost.

On the other hand, although the drum index and CSR of the wood briquette charcoal are not as high as the general values of conventional coke, both values were higher than those of carbonized rice husk briquettes. Based on this, in addition to releasing heat, wood briquette charcoal is expected to function as a substitute for coke in the packed bed at the furnace bottom.

3.2 Test Method in Commercial Plant

A commercial plant test, in which consumption of conventional coke was reduced by using biomass solid fuels, was conducted at No. 1 line of the waste incineration facility at the ECO CLEANCENTER of the Hamada District Regional Administrative Association (Treatment capacity: 49 t/d × 2 lines). Rice husk briquettes and wood briquette charcoal were used as biomass solid fuels.

The most serious concern when attempting to reduce consumption of conventional coke by using biomass solid fuels is difficulty in melting and discharging slag if the heat provided by the biomass fuel is inadequate to melt the slag in the furnace bottom. Therefore, in these tests, the condition of slag discharge was monitored as the use ratio of biomass was increased, and charging of conventional coke was reduced in such a way that the slag temperature did not fall below the standard value.

3.3 Discussion and Evaluation of Results

3.3.1 Index for evaluation of coke reduction

In evaluating the results of these tests, the biomass ratio R_B (%) and the reduction ratio of coke consumption $R_{\Delta C}$ (%) are defined as follows:

$$R_B = B/C_0 \times 100 \quad (1)$$

$$R_{\Delta C} = (C_0 - C)/C_0 \times 100 \cdots\cdots (2)$$

where C_0 (kg/t-waste) is unit consumption of conventional coke under the standard condition (operation using only conventional coke), and C (kg/t-waste) and B (kg/t-waste) are unit consumption of conventional coke and biomass solid fuel under test conditions, respectively.

The relationship between $R_{\Delta C}$ and R_B is important for evaluating the biomass solid fuels.

3.3.2 Coke reduction effect of rice husk briquettes

The test results when using rice husk briquettes as a biomass solid fuel are shown in **Fig. 2**.

Although a maximum reduction ratio of coke $R_{\Delta C}$ of 67% was obtained when the biomass ratio R_B was 160% or higher, marginal increases in $R_{\Delta C}$ were retarded when R_B exceeded 120%. Therefore, a use ratio of 120% or less is economical when using rice husk briquettes.

Figure 2 also shows that a linear relationship exists between $R_{\Delta C}$ and R_B, assuming that use of conventional coke is reduced by an amount equivalent to the heating value of the charge biomass solid fuel. It can be understood that the plots for the case of R_B = 120% or less are virtually all positioned above this line.

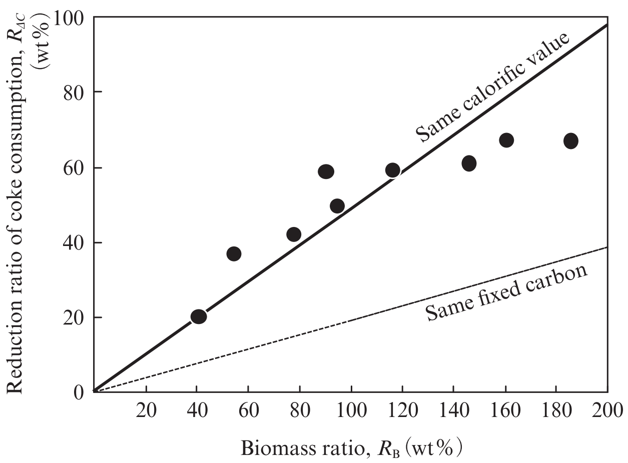

Fig. 2 Reduction ratio of coke consumption for rice husk briquette

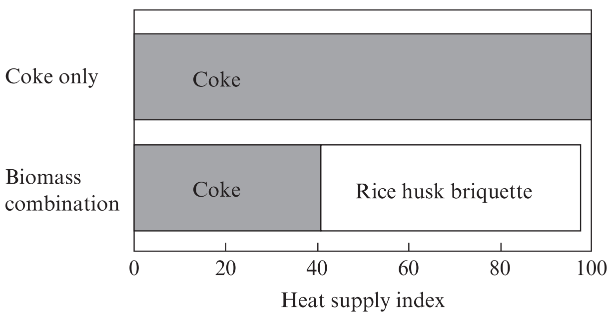

Fig. 3 Heat supply index on using rice husk briquette

Figure 3 shows the heat supply index values for the case of R_B = 120%. The heat supply index is defined as the total heat supplied by conventional coke and biomass solid fuel in the tests when the heat supplied by conventional coke in the standard case is set to 100. Because the heat supply index when using rice husk briquettes is less than 100, this showed that the heat of the rice husk briquettes is used more effectively than that of the conventional coke.

From the results presented above, it is considered that the heat originating from the volatile matter in the rice husk briquettes contributes to reduction of coke consumption, and furthermore, the heating value of the rice husk briquettes is also used more effectively than that of the conventional coke in melting ash in the furnace bottom. Similar effective utilization of heat in the high-temperature gasifying and direct melting furnace can also be expected with other biomass solid fuels.

3.3.3 Coke reduction effect of wood briquette charcoal

The results of the test when using wood briquette charcoal as a biomass solid fuel are shown in **Fig. 4**. Figure 4 also shows that a linear relationship exists between $R_{\Delta C}$ and R_B, assuming that use of conventional coke is reduced by an amount equivalent to the heating value of the charged biomass solid fuel. When R_B was 40% or less, consumption of conventional coke was reduced by an amount substantially equivalent to the heating value of the charged wood briquette charcoal. Because the plots when R_B exceeded 40% were positioned below this line, it can be understood that a weight of biomass fuel larger than the equivalent calorific value must be charged. However, unlike the case of rice husk briquettes, the reduction ratio of coke consumption $R_{\Delta C}$ continues to increase as R_B is increased, and a maximum 100% reduction of conventional coke is possible. In

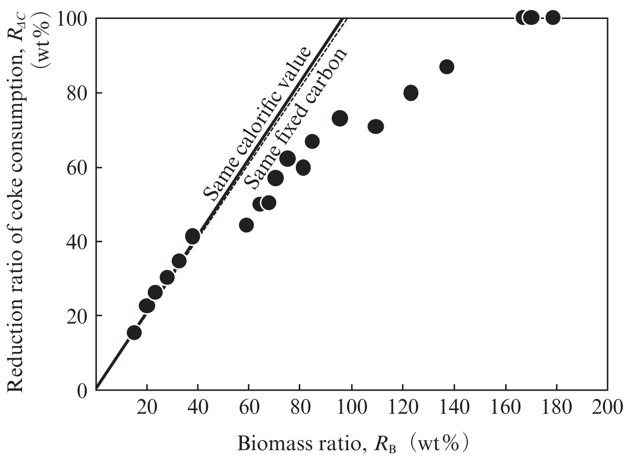

Fig. 4 Reduction ratio of coke consumption for wood briquette charcoal

other words, this test demonstrated that operation without coke is possible when using biomass solid fuel.

The conventional coke which is charged into the high-temperature gasifying and direct melting furnace has the dual functions of providing a heat source for melting ash and forming a packed bed which enables smooth descent of the molten slag. As mentioned previously, the rice husk briquettes are expected to perform an alternate heat source function, but we predicted that this material would not function as a packed bed material due to its low strength after carbonization. Nevertheless, it was possible to replace approximately 60% of the conventional coke with rice husk briquettes. This replaced coke is presumably consumed as a heat source. Likewise, it was also possible to replace up to about 60% of the conventional coke efficiently with wood briquette charcoal in the same manner. Efficiency decreased when replacement with rice husk briquettes was continued into the region where the coke is considered to function as a packed bed material. It can be conjectured that this decrease is due to the low strength of the rice husk briquettes under high temperature conditions in comparison with conventional coke, and the accompanying early consumption. Therefore, if it is possible to use a higher strength carbonized material, it should be possible to replace 100% of the conventional coke with a smaller amount of charged biomass solid fuel.

3.3.4 Cokeless operation by combination of wood briquette charcoal and rice husk briquettes

Because carbonized biomass fuels are generally expensive, it is economical to limit their use to the minimum amount necessary to replace the coke in the packed bed which is formed in the furnace bottom, and to use an inexpensive noncarbonized biomass fuel as the heat source for melting ash. Therefore, in this study, use of a combination of wood briquette charcoal and rice husk briquettes was attempted.

As described in Section 3.3.3, 100% of coke was replaced with wood briquette charcoal. While maintaining this condition, that is, a condition in which 100% of coke is substituted with wood briquette charcoal, part of the wood briquette charcoal was replaced with rice husk briquettes. The results are shown in **Fig. 5**.

Here, the noncarbonized biomass ratio R_B’ (%) and the reduction ratio of carbonized biomass consumption $R_{\Delta C}$’ (%) are defined as follows:

$$R_B' = B'/C_0' \times 100 \cdots\cdots (3)$$

$$R_{\Delta C}' = (C_0' - C') \times 100 \cdots\cdots (4)$$

where C_0’ (kg/t-waste) is unit consumption of wood briquette charcoal in the standard condition (operation using only wood briquette charcoal), and C’ (kg/t-waste) and B’ (kg/t-waste) are unit consumption of wood briquette charcoal and rice husk briquettes in the tests, respectively.

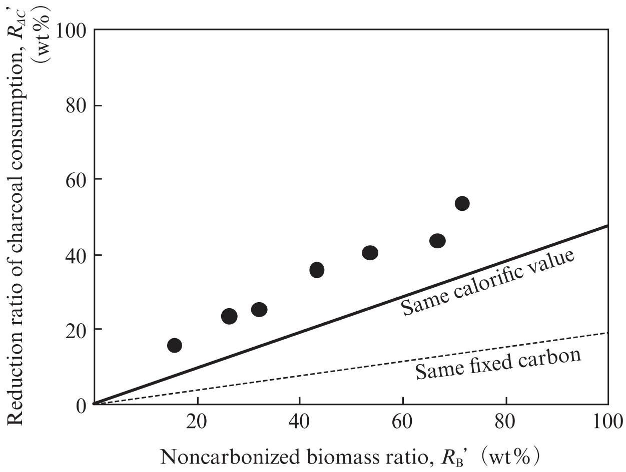

Fig. 5 Reduction ratio of wood briquette charcoal consumption for rice husk briquette

The value of $R_{\Delta C}$’ increased when the amount of charged rice husk briquettes was increased, that is, when R_B’ was increased, and a maximum of more than 50% of wood briquette charcoal was reduced while maintaining 100% substitution for conventional coke.

Figure 5 also shows that a linear relationship exists between $R_{\Delta C}$’ and R_B’, assuming reduction of the carbonized biomass by an amount equivalent to the heating value of the charged noncarbonized biomass. Because all the plots are positioned above this line, it can be understood that heat is used more effectively with the rice husk briquettes than with wood briquette charcoal.

3.3.5 Temperature and quality of slag

In this series of tests, the mean temperature of the slag was maintained on the same level, namely, 1 400°C, which is the guideline for stable operation, and the condition of continuous slag discharge was satisfactory. The slag was sampled in these tests, and Pb elution tests were performed. The results were below the limit of quantitation. Thus, these results confirmed that use of rice husk briquettes and wood briquette charcoal does not affect the amount of eluted Pb from the slag.

3.3.6 CO_2 reduction effect

A trial calculation of the CO_2 reduction effect was made based on the results of these tests. Assuming that annual coke consumption is 1 000 t/year, the carbon concentration of the coke is 85%, and the reduction ratio of coke is 50%, the annual CO_2 reduction is calculated to be 1 550 t-CO_2/year.

4. Natural Gas Injection Test

4.1 Study of Operating Conditions during City Gas Injection

A model of the heat/mass balance in the slag melting zone in the tuyere zone was prepared in order to estimate the coke substitution rate and the theoretical combustion temperature in front of the tuyere when conducting a test of city gas injection from the main tuyere of the high temperature gasification and direct melting furnace. The reactions which were considered in this model are shown in Eqs. (5)–(9).

$$C + 1/2\ O_2 \rightarrow CO \quad (5)$$

$$C + O_2 \rightarrow CO_2 \quad (6)$$

$$H_2 + 1/2\ O_2 \rightarrow H_2O \quad (7)$$

$$CH_4 \rightarrow C + 2H_2 \quad (8)$$

$$C_3H_8 \rightarrow 3C + 4H_2 \quad (9)$$

The composition of the city gas was adjusted so that the heating value was substantially the same as that of actual city gas, considering CH_4 and C_3H_8, which are the main components of city gas, and the calculation was made assuming contents of 91% and 9%, respectively. It was assumed that the city gas injected from the tuyere underwent pyrolysis by the reactions shown in Eqs. (8) and (9) immediately after injection. The portion of H_2 generated by this reaction which reacted according to Eq. (7) was defined as hydrogen reaction rate, α(%). The oxygen injected from the main tuyere first reacted with hydrogen, and the remaining oxygen then reacted with the carbon generated by pyrolysis according to Eqs. (8) and (9). The oxygen which still remained in the system reacted with the carbon of the coke. Although this carbon and oxygen reacted in accordance with Eq. (5) or (6), of the remaining oxygen, the portion that reacted according to Eq. (6) was defined as β(%).

Figure 6 shows the coke substitution rate obtained by calculations for cases using various values of α and β. The predicted coke substitution rate is in the range of approximately 1.0 to 2.7 (kg-coke/kg-city gas).

Since the values of α and β in the actual furnace are not known, the relationship between the theoretical combustion temperature in the tuyere zone and the city gas use rate was obtained assuming hypothetically that α = 50% and β = 50%. The results are shown in **Fig. 7**. The city gas use ratio, R_{NG}, on the x-axis was defined by Eq. (10), which is shown below. Because the theoretical combustion temperature in the tuyere zone decreases greatly as the city gas use ratio increases, it is necessary to increase the oxygen enrichment at the tuyere mouth in order to prevent a decrease in the theoretical combustion temperature in the tuyere zone in test operation.

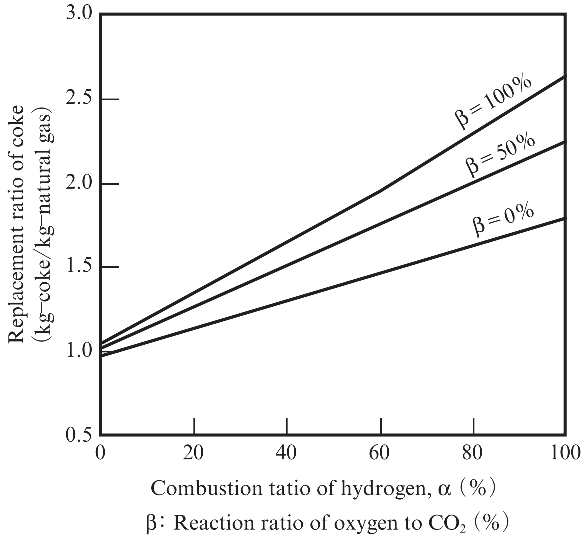

Fig. 6 Prediction of natural gas injection operation

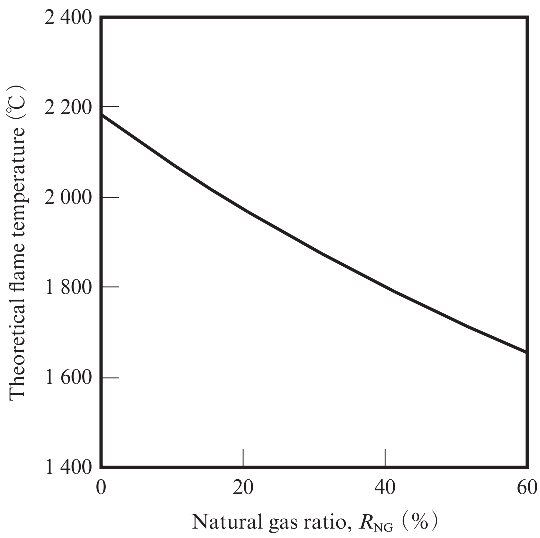

Fig. 7 Change in theoretical flame temperature

4.2 Test Method

A test of reduction in which conventional coke consumption was reduced by injecting natural gas was performed at an actual waste treatment using city gas. The test was carried out over a period of approximately 1 month at a high temperature gasifying and direct melting furnace (Treatment capacity: 314 t/d × 1 furnace) at Fukuyama Recycle Power Co., Ltd. City gas, together with oxygen-enriched air, was injected through the main tuyere.

The composition of the city gas used in this test is shown in **Table 3**. During the test, the amount of city gas injection was gradually increased, and the oxygen

Table 3 Natural gas content

CH_4 (%)	87.1
C_2H_6 (%)	6.6
C_3H_8 (%)	4.6
C_4H_{10} (%)	1.4
N_2 (%)	0.3

enrichment ratio of the oxygen-enriched air from the main tuyere was increased and the amount of conventional coke use ratio was decreased while confirming the condition of slag discharge.

4.3 Results and Discussion

In evaluating the test results, the natural gas use ratio R_{NG} (%) and the conventional coke reduction ratio $R_{\Delta C}$ (%) were defined as follows.

$$R_{NG} = C_{NG}/C_0 \times 100 \cdots\cdots (10)$$

$$R_{\Delta C} = (C_0 - C)/C_0 \times 100 \cdots\cdots (2)$$

Where, C_0 is unit consumption (kg/t-waste) of conventional coke under the base condition (operation using only conventional coke), C is unit consumption (kg/t-waste) of conventional coke during the test, and C_{NG} is unit consumption (kg/t-waste) of natural gas during the test.

The relationship between the conventional coke reduction ratio and the natural gas use ratio in the natural gas injection test is shown in **Fig. 8**. The reduction ratio of conventional coke reached approximately 60%, demonstrating that a substantial reduction of the coke use ratio is possible by injecting natural gas from the main tuyere. Furthermore, Fig. 8 also showed that a linear relationship with R_{NG} exists, assuming reduction of

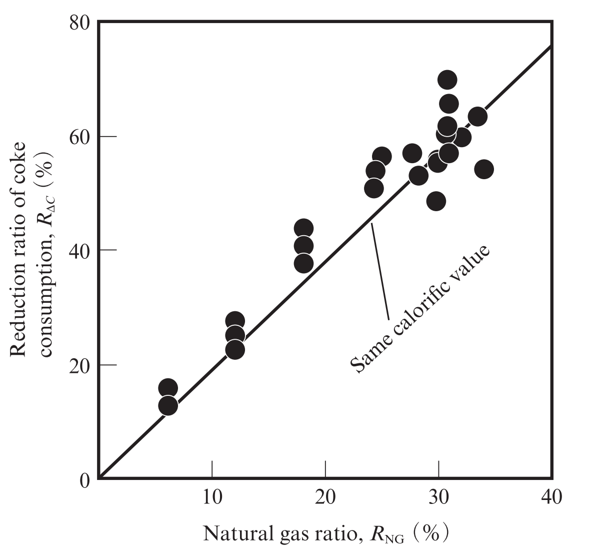

Fig. 8 Reduction ratio of coke consumption for natural gas

conventional coke by heating value equivalent to that of the injected natural gas. The test results are generally above the line showing the equivalent heating value, which indicates that conventional coke can be replaced with city gas at the equivalent heating value.

5. Conclusions

In response to increasing social demand for reduction of CO_2 emissions, plant-scale tests in which use of conventional coke was reduced by using biomass solid fuel and fuel gas were conducted at an actual high-temperature gasifying and direct melting furnace. The biomass solid fuels used in this research were inexpensive rice husk briquettes, followed by wood briquette charcoal, which is comparatively more expensive, but is readily available and maintains its strength in the high temperature environment of the incineration furnace. The fuel gas used in these tests was natural gas, which is also readily available. The results are summarized below.

(1) The rice husk briquettes reach the bottom of the furnace while retaining not only their fixed carbon content, but also their volatile matter, and thus can be effectively utilized as a heat source for melting ash. It was possible to substitute the conventional coke used in the furnace with rice husk briquettes having an equivalent calorific value. A coke reduction of more than 50% was achieved, demonstrating that a substantial reduction in CO_2 emissions is possible. The effects of the rice husk briquettes can also be expected with a diverse range of other biomass solid fuels.

(2) This research also demonstrated that operation without coke is possible when using wood briquette charcoal. This means that it is possible to replace the coke which is used to form a packed bed in the furnace bottom with wood briquette charcoal.

(3) The wood briquette charcoal has the dual functions of providing a heat source for melting ash and forming a packed bed. In the function of heat source for melting, it is possible to replace wood briquette charcoal with low-cost rice husk briquettes. The use ratio of carbonized woody briquettes, which are relatively expensive, can be reduced by more than 50% by combined operation with rice husk briquettes.

(4) The results showed that fuel gas can be used effectively as a heat source for melting incineration ash by supplying city gas from the main tuyere in the furnace bottom. It was possible to substitute conventional coke with city gas of the equivalent heating value. A conventional coke reduction ratio of approximately 60% was achieved, demonstrating that a substantial reduction in the use of conventional coke is possible.

The high-temperature gasifying and direct melting furnace currently uses coke to melt the ash of waste. However, this research demonstrated that this furnace has excellent fuel flexibility, as at least half or more of the coke can be replaced with biomass solid fuels or fuel gas. Although the availability of these fuels will vary depending on the region, more economical operation is possible by substitution of coke alternatives, using the optimum combination for each facility. The authors are now studying the cost and supply stability of biomass solid fuels and fuel gases with the aim of practical application.

The authors wish to express their appreciation to all those concerned at the Hamada District Regional Administrative Association and Fukuyama Recycle Power Co., Ltd. for their generous cooperation in these tests.

References

1) Suzuki, A.; Nagayama, S. High efficiency WtE power plant using High-Temperature Gasifying and Direct Melting Furnace. Proceedings of Sardinia 2011, The Thirteenth International Waste Management and Landfill Symposium. Sardinia, 2011-10-03–07, EUROWASTE Srl. Padova, IT.
2) Uchiyama, T.; Okuyama, K.; Nakayama, T.; Watanabe J.; Akiyama H.; Suzuki Y.; Oda, H.; Hoshi, Y.; Murata, H.; Tanaka, K.; Ida, T. Decrease in CO_2 Emission by Using Bio-Coke at High-Temperature Gasifying and Direct Melting Furnace. Transactions of the Japan Society of Mechanical Engineers, Series (B). 2012, vol. 78, no. 789, p. 1008–1011.
3) Ida, T. The Technical Production Development of Advanced Alternative Coke Fuel, Bio-coke, by Non-carbonized Transfer Technology. Journal of the Japan Institute of Energy. 2011, vol. 90, no. 1, p. 2–9.