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Demonstration of Zero-Coke Operation and Biomass Charcoal Performance Verification in High-Temperature Gasifying and Direct Melting Furnace

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Abstract:

The high-temperature gasifying and direct melting furnace uses coal-derived coke as an auxiliary fuel to melt ash. The performance of biomass charcoal as a substitute for coke was studied using a demonstration facility in Singapore. The results showed that biomass charcoal can successfully be fully substituted for coal-derived coke at comparable consumption rates. A maximum charcoal consumption ratio of 1.5 was obtained through the evaluation of four different types of biomass charcoal from suppliers across Southeast Asia. This study also found the following minimum requirements for suitable biomass charcoal: Apparent density of more than 0.94 g/cm^3 (dry basis), volatile matter content of less than 7 %wt. (dry basis) and weight per piece of more than 90 g (dry basis). In addition, when two types of charcoal are mixed, it was found that the total consumption rate is not the mean value between the two types of charcoal, but decreased toward the value of the higher performance charcoal. These results represent an encouraging step toward zero-coke operation aimed at carbon neutrality, as well as the diversification of suitable biomass charcoal in order to secure its stable sourcing in the commercial stage.

1. Introduction

Initiatives to achieve carbon neutrality are being promoted worldwide. To pursue decarbonization, it is necessary to reduce the use of fossil fuels, especially coal-based fuel, and replace them with renewable energy resources.

The JFE high-temperature gasifying and direct melting furnace uses coke to convert waste into gas and melt ash, and is capable of treating general waste, industrial waste, incineration ash, excavated waste, asbestos, and various other types of waste. This furnace has been delivered to 13 plants in Japan and overseas$^{1)}$ since the first unit was constructed in 2003. As this process was developed based on blast furnace technologies utilized in the ironmaking process, it uses coal-derived coke (hereinafter, "coke"). For this reason, experiments have been performed using an actual furnace with the aim of replacing coke with biomass fuel.$^{2, 3)}$ Since charcoal has been used as a fuel for ironmaking in areas where raw wood is easier to obtain than coke,$^{4)}$ the idea of completely replacing coke with biomass fuel in blast furnaces is fairly realistic. It is also important to strike a balance between environmental friendliness and economic efficiency by selecting and adopting fuels that are inexpensive and available in each region.

In Singapore, where final landfill space is becoming scarce, the recycling of waste incineration ash is treated as an urgent issue, and the country is willing to adopt advanced waste treatment approaches. JFE Engineering concluded a joint research contract on next-generation waste treatment technology with Nanyang Technological University of Singapore, and in 2019, constructed a high-temperature gasifying and direct melting furnace demonstration facility (Waste-to-Energy Research Facility; hereinafter, "WTERF") at the request of the university. Because the government of Singapore prohibits the commercial import of coke in line with its carbon neutrality policy, it is a requirement that coke be replaced entirely with biomass fuel. Under this joint research contract, verification tests have been performed at WTERF.

This paper describes the knowledge concerning the replacement of coke with biomass carbonized fuel (hereinafter, "biomass charcoal") obtained through

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these demonstration tests in Singapore. As biomass fuel can be obtained easily in Singapore for geographical reasons, the authors have been performing tests in which coke is completely replaced with biomass charcoal to verify zero-coke operation while evolving the coke replacement technology developed in Japan. Further, to address the challenge of securing the required volume of biomass charcoal toward commercialization, the consumption of various biomass charcoal products was evaluated under conditions of single use or use in combination with other biomass charcoal products to pursue diversification. This paper presents the results of these tests.

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

Fig. 1 shows a cross-sectional view of the JFE high-temperature gasifying and direct melting furnace. Oxygen-enriched air is blown in through the main tuyere in the lower part of the furnace, air is blown through the secondary tuyere in the middle of the furnace, and waste, coke and limestone are charged from the top of the furnace. The water content evaporates in the uppermost part of the waste layer deposited in the melting furnace, while thermal decomposition of the combustible component takes place directly beneath it. The fixed carbon and ash content of the waste are preheated while descending through the melting furnace together with the charged coke and limestone. During this time, the fixed carbon is burnt and gasified by the O_2 and high-temperature CO_2 flowing up from the bottom of the furnace, and the ash content reaches the bottom of the furnace together with coke and limestone.

While the waste burns out in a short time in the furnace bottom, consumption of the coke requires a longer time, and the remaining coke accumulates on the furnace bottom to form a packed bed. In the coke-packed bed, coke is incinerated with oxygen-enriched air supplied from the main tuyere, and ash is melted by the heat generated by combustion. At this time, the limestone lowers the melting point of the ash and the viscosity of the generated molten slag while also improving flowability. The molten slag flows down through the coke-packed bed and is continuously discharged through the slag discharge port.

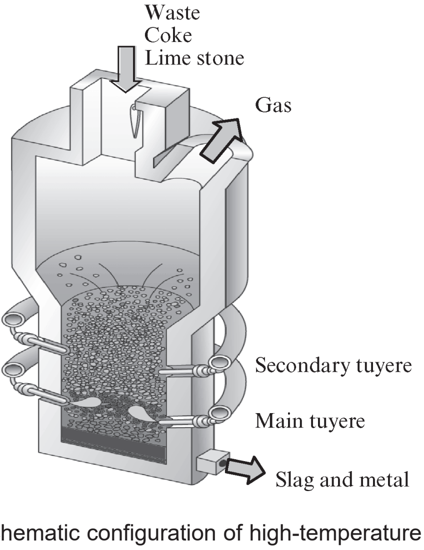

Fig. 1 Schematic configuration of high-temperature gasifying and direct melting furnace

The total amount of oxygen blown in through the main tuyere and the secondary tuyere is too small to completely incinerate the charged waste, which causes the generation of a combustible gas containing CO and H_2. The combustible gas generated in the waste layer is completely burnt out in the secondary combustion chamber following the melting furnace. The heat of the incinerated gas is recovered in the boiler, and the gas is transferred to the exhaust gas treatment system.

3. Overview of Biomass Charcoal

3.1 Selection of Biomass Charcoal

In order to completely replace coke, biomass charcoal must have properties similar to those of coke. It is desirable to have a product that is well carbonized, high in density and large. One type of biomass charcoal is carbonized wood dust briquette, which is made by extruding discharged sawdust and molding it into a hexagonal or square columnar shape, then carbonizing it at a high temperature. This is a commercially available product and is widely used as a substitute for the expensive high-grade charcoal called Bincho charcoal. Because it can achieve both the required performance and economic efficiency, this product, which is also called Oga charcoal or sawdust charcoal, is a potential alternative for coke in high-temperature gasifying and direct melting furnaces. However, the quality varies from manufacturer to manufacturer. Of the products that are commercially available in Malaysia and Vietnam, four types of high-quality products were selected as biomass charcoal fuel for high-temperature gasifying and direct melting furnaces. **Photo 1** shows the appear-

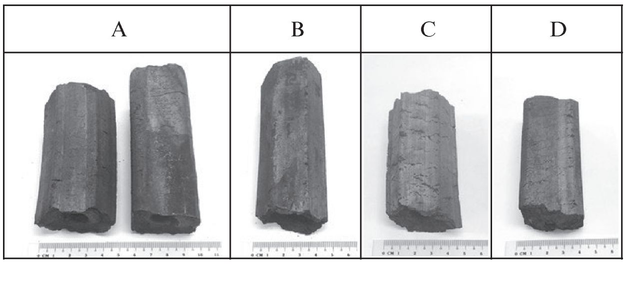

Photo 1 Biomass charcoals

Table 1 Properties of biomass charcoals

Type			Saw dust charcoal					Coke
Biomass charcoal name			A		B	C	D	
Size		(mm)	φ48 × L80	□39 × L80	φ43 × L80	φ44 × L80	□37 × L80	40～80
Weight*		(g-dry/piece)	103	99	91	85	100	40～400
Proximate analysis	Moisture	(wt%-dry)	6.7		8.5	8.6	9.5	1～6
	Ash	(wt%-dry)	2.3		4.2	5.5	6.4	10～13
	Volatile matter	(wt%-dry)	3.6		4.3	6.9	6.1	0.3～2
	Fixed carbon	(wt%-dry)	94.1		91.5	87.6	87.5	85～89
Lower calorific value		(MJ/kg)	30.3		28.9	28.1	26.5	27～30
Apparent density (dry basis)		(g/cm^3)	0.94		1.00	0.94	1.02	1.0～1.2

＊Weight of saw dust charcoal is converted to 80 mm in length

ance of these products. Biomass Charcoal A is made in Malaysia, and Biomass Charcoals B, C and D are made in Vietnam. Biomass Charcoal D is an improved version of Biomass Charcoal C.

A good quality sawdust charcoal is normally formed into a long stick product. However, to avoid the formation of bridges in the hopper and other facilities, cutting the product into pieces with a length of about 80 mm was specified as an exception.

3.2 Comparison of Properties of Biomass Charcoal Products

Table 1 shows the result of a comparison of the properties of coke and the four biomass charcoal products. All biomass charcoal products consist of 80 wt% (dry basis) or more of fixed carbon, which is the same as in coke. Since the ash content of raw biomass is generally lower than that of coal, the ash content of biomass charcoal products is lower than that of coke.

The shape of the biomass charcoal affects the consumption rate. Since the coke and biomass charcoal at the bottom of the furnace are incinerated due to surface reactions, the consumption rate decreases as the size of individual lumps becomes larger and the specific surface area becomes smaller. The size of individual lumps can be determined simply by using the weight per piece. Table 1 shows the weight when the products were cut into pieces 80 mm in length.

The volatile matter content and apparent density are important factors that affect the strength and consumption rate of biomass charcoal in the furnace. The apparent densities shown in Table 1 were calculated using the dry weight and the displaced volume of water in accordance with JIS K 2151. To form a good packed bed in the lower part of the high-temperature gasifying and direct melting furnace with as little feed as possible, it is desirable to have biomass charcoal with increased strength that reacts at a low speed so the residence time in the furnace is long. When biomass charcoal has a high volatile matter content, the volatile matter evaporates rapidly when exposed to high temperatures, which increases the porosity of the charcoal, resulting in reduced strength and an increase in the reaction speed. Biomass charcoal with a low volatile matter content and high apparent density can maintain its strength even under high temperatures, suppressing the reaction and consumption speed.

Biomass Charcoal A is slightly larger than the other charcoals, and its dry weight per piece is 103 g in a hexagonal column and 99 g in a square column. Its volatile matter content is less than 5 wt% (dry basis), and its apparent dry density is 0.9 g/cm^3 or more.

Biomass Charcoal B is slightly smaller in diameter than Biomass Charcoal A, with a dry weight per piece of 91 g. Its volatile matter content is similar to that of Biomass Charcoal A, although the value is slightly higher, and it has a significantly higher apparent density of 1.00 g/cm^3, which is close to the density of coke.

The diameter of Biomass Charcoal C is slightly smaller than that of Biomass Charcoal A and slightly larger than that of Biomass Charcoal B, but since its apparent density is low, the dry weight per piece is also low, at 85 g (dry basis). Its volatile matter content is slightly higher than those of Biomass Charcoals A and B, and its apparent density is similar to that of Biomass Charcoal A.

Biomass Charcoal D is an improved version of Biomass Charcoal C. Although its volatile matter content was decreased only slightly from that of Biomass Charcoal C, its dry weight per piece was increased to 100 g (dry basis), a value equal to that of Biomass Charcoal A, and the apparent density of the product was improved, exceeding the 1.00 g/cm^3 (dry basis) of Biomass Charcoal B.

4. Demonstration Test Toward Zero-Coke Operation

4.1 Test Method

A series of tests was performed using the selected biomass charcoals at WTERF (treatment capacity of 11.5 t/day × 1 furnace), which is shown in **Photo 2**.

4.1.1 Complete Replacement of Coke with Biomass Charcoal

Biomass Charcoal A was used in the test to replace coke. In the demonstration facility, first, the conditions for stable operation were determined using coke, after which the amount of coke was reduced gradually while charging Biomass Charcoal A so that the slag temperature would not fall below the standard value. After complete replacement of coke was achieved, operation was continued for one month to ensure stable operation. The amount of biomass charcoal used was then reduced further to determine the standard operating conditions.

4.1.2 Determining Unit Consumption of Each Biomass Charcoal

Next, a test was performed to compare Biomass Charcoal A with the other biomass charcoals. The amounts used were 20 t each of Biomass Charcoal B and C and 10 t of Biomass Charcoal D. The fuel consumption in the demonstration test was confirmed by switching the type of biomass charcoal feed all at once, and then controlling the amount of biomass charcoal supplied so as to maintain a good ash melting condition and keep the slag temperature from falling below the standard value.

Photo 2 High-temperature gasifying and direct melting furnace demonstration facility

4.1.3 Combined Use of Biomass Charcoal Products

The demonstration facility has two feeders, one for coke and the other for biomass charcoal. Once the coke has been completely replaced, coke feed is no longer required and it becomes possible to feed two types of biomass charcoal. Since various types of biomass charcoal with different performances are expected to be used in combination in commercial furnace applications, the effect of combined use was verified. As will be described later, Biomass Charcoal B and C, which differ greatly in performance, were used to observe the change in fuel consumption by changing the mixing ratio of the two.

4.2 Test Results

In this test, fuel consumption was evaluated by dividing the unit consumption of each type of fuel by the unit consumption of fuel used during operation with coke, and is expressed by the fuel consumption ratio (fuel unit consumption index) R_f (wt%).

$$R_f = F/C_0 \times 100 \quad \cdots\cdots (1)$$

Where C_0 is the unit consumption of coke (kg/t-waste) during standard operation with coke only, and F is the unit consumption of each type of fuel (kg/t-waste) used in this test.

4.2.1 Complete Replacement of Coke with Biomass Charcoal

In the series of tests where the operating conditions started with the stable conditions using coke, Biomass Charcoal A was fed to replace the coke, and the standard operating conditions were determined at the end. **Fig. 2** shows the change of the fuel consumption ratio over time in these tests, and **Fig. 3** shows the change of slag temperature over time.

Biomass Charcoal A was gradually increased over a period of about one month, as shown in Fig. 2 (1), and the coke was gradually reduced in proportion until all of the coke was replaced with charcoal. Although the consumption ratio of Biomass Charcoal A reached 136 wt%, the fact that the slag temperature continued to increase slightly while the coke was being replaced, as shown in Fig. 3 (1), suggests that excessive heat was applied in the set conditions in anticipation of unforeseeable circumstances.

Then, the conditions under which complete replacement of coke was achieved were maintained for one month for a continuous operation test. The fuel consumption ratio during the period shown in Fig. 2 (2) and the change in the slag temperature shown in Fig. 3

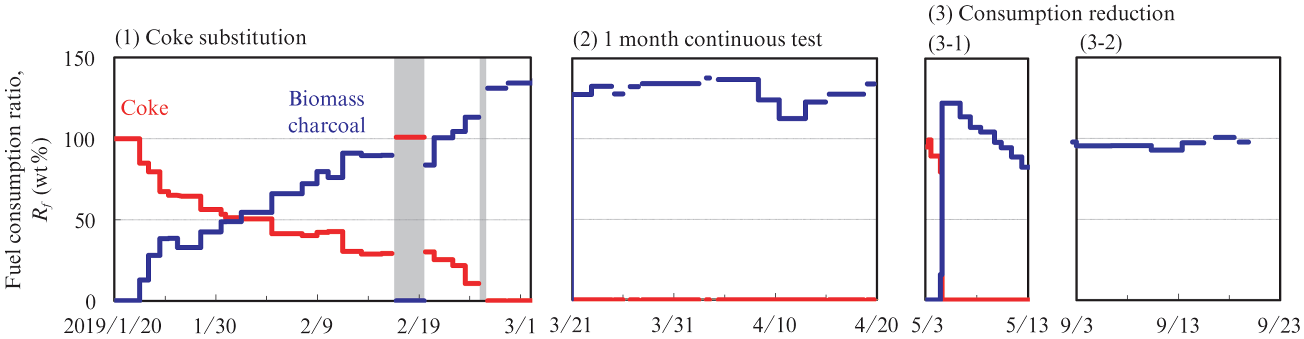

Fig. 2 Time-dependent change of fuel consumption ratio in full coke substitution of biomass charcoal A

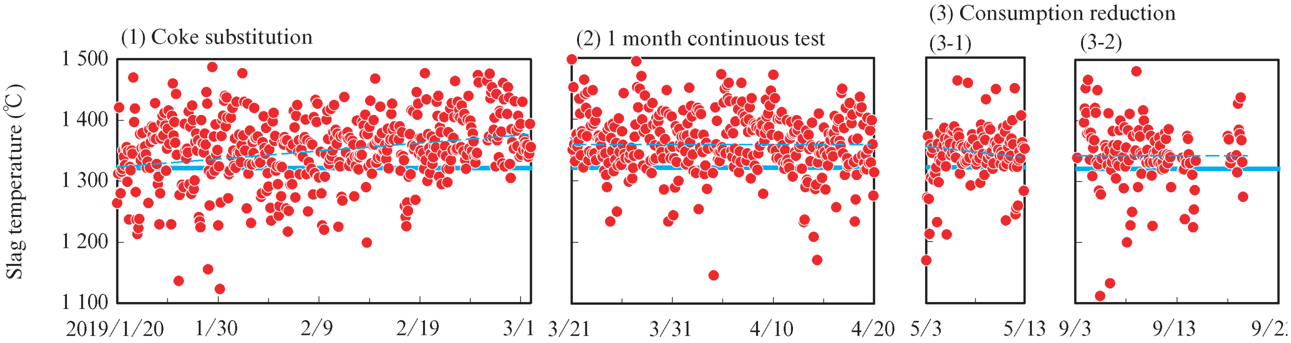

Fig. 3 Time-dependent change of slag temperature in full coke substitution of biomass charcoal A

(2) prove that stable operation for an extended period of time can also be achieved with single use of Biomass Charcoal A. During this period, a very good furnace operating condition was maintained, and continuous operation was successful. In addition, feeding of biomass charcoal was reduced on a trial basis for a short period of time during the continuous operation test, confirming that feeding can be reduced further.

After the continuous operation test was completed, another test was performed separately with a lower feeding rate of Biomass Charcoal A. Fig. 2 (3–1) shows the change of the fuel consumption ratio over time. When the consumption ratio reached around 83 wt%, fluctuations in the supply of waste and fuel hampered the continuous discharge of slag and discharge frequently stopped, so the lower limit of feeding was set to that value. Fig. 3 (3–1) shows the temperature of the slag during the test, and indicates that the temperature drops as the biomass charcoal feed rate is reduced. After that, as shown in Fig. 2 (3–2), feeding of Biomass Charcoal A continued at a fuel consumption ratio of 99 wt%, at which stable slag discharge was secured, proving that continuous stable operation is possible for two weeks. The slag temperature shown in Fig. 3 (3–2) is similar to that during operation with coke only. Thus, this testing verified that Biomass Charcoal A can ensure operation as stable as that with coke when using a feeding rate of 99 wt%, which is almost equal to the feeding rate of coke.

As described above, zero-coke operation, that is, complete replacement of coke, was achieved by feeding the same weight of biomass charcoal as in operation with coke. At present, coke is not prepared for use in the demonstration facility in Singapore, and biomass charcoal is normally used in operation.

4.2.2 Determining Unit Consumption of Each Type of Biomass Charcoal and Key Factors

Various tests were started at the demonstration facility using the standard conditions determined through the tests for complete replacement of coke described above. **Fig. 4** shows the fuel consumption ratios of the four biomass charcoal products shown in

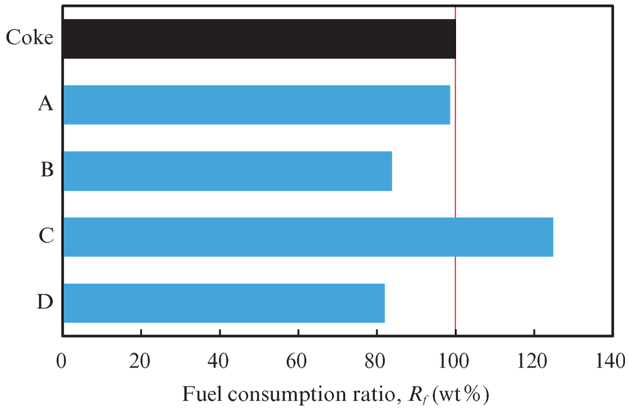

Fig. 4 Fuel consumption ratio of biomass charcoals

Table 1 when used individually and adjusted to achieve the same slag temperature level. The fuel consumption ratio varies greatly depending on the type of biomass charcoal.

The fuel consumption ratio of Biomass Charcoal A is 99 wt%, which is almost equal to that of coke, as noted above. Since the fuel consumption ratio of Biomass Charcoal B is 84 wt%, use of this charcoal as a fuel will reduce the fuel consumption ratio by 15% compared to operation using Biomass Charcoal A. Biomass Charcoal B is superior to Biomass Charcoal A in apparent density, which means that the fuel consumption ratio can be reduced effectively by increasing the apparent density of the charcoal.

The fuel consumption ratio of Biomass Charcoal C is 125 wt%, which is 26% higher than that of Biomass Charcoal A and equal to 1.5 times the fuel consumption ratio of Biomass Charcoal B. The weight per piece of Biomass Charcoal C is smaller than that of Biomass Charcoal A, and its apparent density is lower than that of Biomass Charcoal B. These factors presumably had a total effect that caused deterioration of the fuel consumption ratio of Biomass Charcoal C. The volatile matter content of Biomass Charcoal C is 6.9 wt% (dry basis), as shown in Table 1, which is slightly higher than the 3.6 wt% (dry basis) of Biomass Charcoal A. A lower volatile matter content is more desirable, but considering the fact that a good fuel consumption ratio was achieved with Biomass Charcoal D, which contains 6.1 wt% (dry basis) of volatile matter, it is unlikely that the slight difference in the volatile matter content was a determinant of the deteriorated fuel consumption ratio.

The fundamental means of improving the fuel consumption ratio of Biomass Charcoal C is to increase the apparent density of the product, which will also result in an increase in weight per piece. The apparent density of Biomass Charcoal D, an improved version of Biomass Charcoal C, is 1.02 g/cm^3 (dry basis), which is higher than the 1.00 g/cm^3 (dry basis) of Biomass Charcoal B, and the weight per piece is 100 g (dry basis), which is almost equal to that of Biomass Charcoal A. The test found that the fuel consumption ratio of Biomass Charcoal D was reduced to 82 wt%, which is 34% smaller than that of Biomass Charcoal C, and the improved Biomass Charcoal D achieved a fuel consumption ratio almost equal to that of Biomass Charcoal B.

The series of tests to determine the unit consumption of fuel revealed that the biomass charcoal to be used in the high-temperature gasifying and direct melting furnace must have an apparent density of 0.94 g/cm^3 (dry basis) or more, and preferably 1.0 g/cm^3 (dry basis) or more, a volatile matter content of 7 wt% (dry basis) or less in the measured value, and a weight per piece of 90 g or more. The biomass charcoal product should also have a length that is about double its diameter. Extending the length to increase the weight per piece is not a desirable solution, as it is estimated that extending the length to more than twice the diameter will have only a limited effect of reducing the specific surface area and will have virtually no effect on reducing consumption by weight, while the longer length will increase the formation of bridges in the hopper and other facilities.

4.2.3 Combined Use of Biomass Charcoal Products

The fuel consumption ratio of Biomass Charcoal C is 1.5 times that of Biomass Charcoal B. The two types of biomass charcoal were fed in the high-temperature gasifying and direct melting furnace and their mixing ratio was adjusted to verify the fuel consumption ratio when they are used in combination. **Fig. 5** shows the results.

The result obtained was not the simple average of the two consumption ratios, but was rather significantly affected by the performance of the higher performance biomass charcoal, achieving a fuel consumption ratio close to that of the higher-performing product. When the high-performance Biomass Charcoal B was partially replaced with Biomass Charcoal C, the increase in the fuel consumption ratio remained small even when about half of Charcoal B was replaced. The fuel consumption ratios of Biomass Charcoal B and C were 84 wt% and 125 wt%, respectively. When they are mixed at a ratio of 50 wt%-50 wt%, the simple average obtained by calculation is 105 wt%, but the measured value is 88 wt%. This means that combined use achieved a reduction of 16 wt% in the consumption of

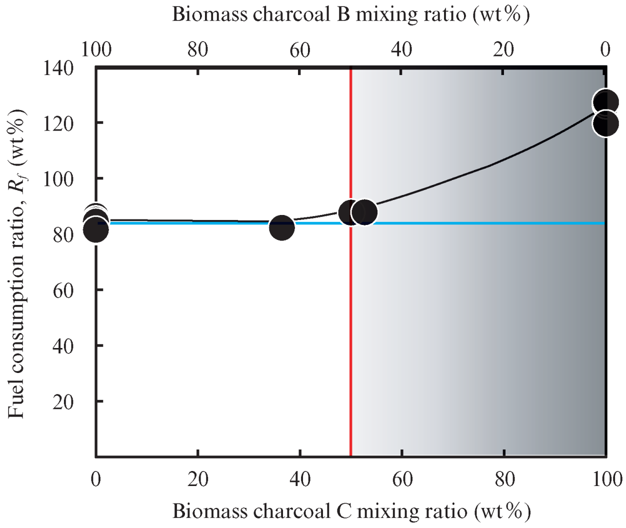

Fig. 5　Fuel consumption ratio of mixed biomass charcoals

biomass charcoal.

Biomass charcoal functions as a heat source for ash melting and as a bed material which forms the ash melting region and enables a smooth downward flow of the molten slag. Of those functions, the heat source function can probably be substituted by a low-performance biomass charcoal product as long as the required amount of heat is maintained. That is, when two kinds of biomass charcoal with different performances are used in combination, the higher-performing one can be replaced as long as a sufficient amount to maintain the function as the bed material is secured while also maintaining a certain amount of heat, and if the calorific values of the two products are almost the same, replacement is possible while keeping the same feeding weight.

5. Procurement of Biomass Charcoal

The examination described above identified the properties of the biomass charcoal that should be selected for the high-temperature gasifying and direct melting furnace, and clarified the future direction of measures to secure the required amount of applicable biomass charcoal.

The properties required in the applicable biomass charcoal were identified first, which made it easier to select the biomass charcoal.

Next, the tests confirmed that the fuel consumption ratio varies depending on the properties of the biomass charcoal products, as shown in Fig. 4, and when different charcoals are used in combination, the fuel consumption ratio is lower than the simple average of the products, as shown in Fig. 5. This verified the fact that the total fuel consumption will be reduced when biomass charcoal products with different properties are used in combination. Therefore, if replacement efficiency is improved by upgrading products at manufacturing plants and by adopting the combined use method, less biomass charcoal will be required at commercial plants, which will make it easier to procure. That is, an increase in the efficiency of biomass charcoal is equivalent to an increase in the amount of biomass procured.

6. Conclusion

In order to achieve carbon neutrality, JFE high-temperature gasifying and direct melting furnaces must avoid using coal-based fuel. To address this requirement, verification tests to enable the complete replacement of coke with biomass charcoal were performed at the Waste-to-Energy Research Facility in Singapore. Four kinds of biomass charcoal products manufactured in Malaysia and Vietnam were selected and tested, and the following results were obtained.

(1) Coke can be completely replaced with biomass charcoal, and stable, long-term operation was achieved with 100% biomass charcoal. It is possible to reduce the consumption of biomass charcoal by weight to the same level as that of coke.

(2) The fuel consumption ratios of the four kinds of biomass charcoal were compared by expressing the consumption ratio as an index of consumption by weight per ton of waste. The maximum difference in the fuel consumption ratios of the four biomass charcoal products was 1.5 times.

(3) The required performance of biomass charcoal applicable to the high-temperature gasifying and direct melting furnace was identified as follows: The apparent density should be 0.94 g/cm^3 (dry basis) or more, and preferably 1.0 g/cm^3 (dry basis) ; the volatile matter content should be 7 wt% (dry basis) or less; and one piece of the biomass charcoal should have a length about double its diameter and a dry weight of 90 g or more.

(4) When two kinds of biomass charcoal were used in combination, the consumption by weight was not the simple average of the two but a value close to the consumption ratio of the higher-performing biomass charcoal. Thus, this study revealed that the total amount of biomass charcoal can be reduced by adopting the combined use method.

As described so far, there has been great progress toward zero- coke operation of commercial furnaces in the aim of achieving carbon neutrality. In the demonstration facility, use of biomass charcoal in place of coke during normal operation has now become the standard practice. In addition, in order to diversify the types of biomass charcoal to be used, the consumption by weight in operation with single and combined use of various kinds of products was verified, which clarified the future direction of measures to secure biomass charcoal. Although the optimum utilization method for inexpensive coke has already been established, JFE Engineering will further expand the application of biomass fuel in actual furnaces and will continue to pursue cost reduction with the aim of using biomass fuel commercially as an alternative to coke.

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