Exergy Analysis of Charcoal Charging Operation of Blast Furnace

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(Received on June 18, 2004; accepted in final form on July 21, 2004)

Effective use of biomass resource is expected to be one of the solutions to the environmental problems, since a sort of biomass absorbs carbon dioxide through photosynthesis reaction. One of the possibilities to utilize such biomass resources is the replacement of coal and/or coke with charcoal. With nature of charcoal it is known that the hot metal quality can be improved as well as abatement of environmental impact through less slag generation and virtually no CO₂ and SO₂ emissions. This paper performed an exergy analysis on charcoal charged blast furnace. As a result, it is revealed that the charcoal system needs more enthalpy and exergy inputs than conventional ironmaking system while it produces more energy available in the other processes. This keeps exergy loss in charcoal system in the comparable level with the conventional system. The analysis shows that each process included in the system still has a possibility to be improved. Thus the performance of the charcoal system is expected to be equivalent to or even better than the conventional system. Therefore ironmaking system with charcoal charged blast furnace is expected to be a key technology to contribute environmental issues.

KEY WORDS: blast furnace; charcoal charging; exergy analysis; carbon dioxide emission; environmental issues; biomass.

1. Introduction

Iron and steelmaking industry uses huge amount of underground resources, like iron ore, coal and limestone. Iron and steel products are accumulated in the municipality, and a portion of their wastes is recycled as a raw material for iron and steel production again. On the contrary, the coal is used as fuel and reductant in the ironmaking process, and the carbon in the coal is finally released to the environments as carbon dioxide, which is included in the six major greenhouse gases, as shown in Fig. 1(a). Therefore, it raises carbon dioxide concentration in atmosphere. In recent years social awareness has been increasing movements to reduce greenhouse gas emissions to prevent global warming. Such social pressure acts strongly to the iron and steelmaking industry due to its huge industrial scale and energy consumption. With such background a lot of countermeasures like improvement of ironmaking process,¹ combination of processes,²–⁶ effective heat recovery,⁷–⁹ and so on have been proposed. Another method to reduce carbon dioxide emission is use of biomass resources. The biomass resources produced through photosynthesis, like woods, grass, sugarcane, etc., fix carbon dioxide within their body during their growth process. Therefore, with effective use of such biomass resources, carbon dioxide emitted from the industry is absorbed by them, and a recirculation route of carbon can be formed as shown in Fig. 1(b).

One of the utilization of biomass resources in ironmaking industry is to make use of charcoal as fuel and reductant. Use of charcoal in the blast furnace has another advantage from conventional process as well as lowering carbon dioxide emission. Sulfur content of charcoal is usually much less than that of coal or coke. This directly results in low sulfur dioxide emission,¹⁰ and allows blast furnace acidic slag operation, and reducing the use of lime or limestone, further more to decrease slag generation. Contrary to such benefits, simply replacing charged coke with charcoal in the large-scale furnace is likely to cause operation trouble because the strength of the charcoal is usually lower than that of coke. As the solutions for such charcoal proper-
ties, there are several methods to use charcoal in the blast furnace process. One of these countermeasures is the pulverized charcoal injection into the furnace through tuyere, and was previously discussed its environmental impact through mass and heat balance of a furnace. This analysis shows that the most carbon dioxide released directly from a blast furnace with pulverized charcoal injection at 200 kg/thm is absorbed by the forest that is planted for charcoal production. Sampaio et al. discussed injection of charcoal fines converted from the city waste biomass to blast furnace tuyere, and resulted that this operation has potential to reduce more than 30% of net carbon dioxide emission compared with traditional ironmaking process. Second one is use of charcoal fines as a raw material of formed charcoke using wood tar as a binder. It is reported that the formed charcoke has enough strength for use in conventional blast furnaces. The third method is replacing coke with lump charcoal in small-scale blast furnace. In the small scale furnace compression stress acting on each charcoal particle is much smaller than that in the larger furnace.

The operation of small blast furnace with charcoal charging has already had many practices in the past, and still continues in some countries. An analysis of the furnace performance can be found elsewhere, detailed analysis of furnace performance based on precise heat and mass balances, however, has yet to be discussed. Furthermore, although effective use of biomass resources reduces net emission of carbon dioxide, the process itself has to work at high efficiency and heat and byproducts need to be utilized for further reduction of greenhouse gas emissions. The exergy analysis is an effective way to clarify process efficiency and the potential energy output from the process. This study performed an exergy analysis on biomass based, namely charcoal charged, blast furnace process based on the practical operation results to examine feasibility of this process.

2. Charcoal Charged Blast Furnace Ironmaking System

2.1. Outline of the System

The ironmaking system with charcoal charged blast furnace considered in this study is depicted in Fig. 2. At first, trees are planted according to their growth rate. During their growth fixation of carbon dioxide from the atmosphere occurs through photosynthesis reaction, and carbon accumulates in the organic framework of the trees while oxygen is released to the atmosphere. Once they grow up to certain size (7 years cycle for eucalyptus trees in Brazil), they are hewed down and sent to carbonization kiln to produce charcoal. The lumber and air are supplied to the kiln. A portion of wood is burned in the kiln to supply heat of carbonization. With increase in temperature moisture of wood evaporates, organic framework pyrolyzes, tar and low molecular weight compounds are released to gas phase, and finally the charcoal is produced. Tar and kiln off gas include hydrocarbons, carbon monoxide, hydrogen, and so on, and are exported outside of the system as chemical raw material or fuel. The charcoal produced in the kiln is sent to a small-size blast furnace with inner volume varying from 60 to 550 m³, and charged with small and medium lump ores and additional flux agents such as limestone and dolomite on to the top of the furnace. Hot blast air is introduced into the furnace through tuyere settled on the lower wall of the furnace. The hot blast air burns the charcoal and generates reducing gas (carbon monoxide and hydrogen) and heat. The iron oxide in the charged ore is reduced by the reducing agent gas and the solid materials are heated up by the contact with hot reducing gas. Finally the reduced iron melts, flows down, accumulates in the hearth, and finally leaves the furnace from a tap hole at the bottom of the furnace. The partially oxidized reductant gas flows out from the top of the furnace. This outflow gas is called top gas or blast furnace gas (BFG). The top gas still contains significant amount of carbon monoxide and hydrogen, and has potential to generate heat. A portion of top gas flows out from the furnace is sent to the air heater (not shown in Fig. 2) to heat up blast gas. The remaining part of the top gas is exported as the fuel gas to be consumed in other processes. The off gas of the air heater heats up the iron ore and flux agents before they are charged to the furnace.

One of the most remarkable features of this system compared to the modern ironmaking systems is excluding sintering and/or pelletizing processes. Charcoal usually contains much less sulfur (typically 100 times lower) in contrast to coal or coke. This allows acid (low basicity) opera-
tion of blast furnace. The ash of charcoal is basic in its nature while the gangue of iron ore is acid in nature. In addition, the blast furnace considered in this study is small. Thus the melting behavior is less crucial because the total pressure drop in the furnace is small. Therefore, the iron ore in the size range of 5 to 15 mm is able to be charged directly as a burden material, and the sintering process is unnecessary in this system any more. With this feature, labor cost and energy consumption for agglomeration process is needless. Another feature of this system is low slag rate. This characteristic is also brought by the natures of charcoal and acid operation, namely low ash content and low additional matter feed. This might contribute to relieve the waste problem.

### 2.2. Operation Status

The system consumes 586.7 kg of charcoal and 1 459 kg of lump ore to produce a ton of hot metal. The operational data of a carbonization kiln is summarized in Table 1. For this charcoal production (586.7 kg), 1 571 kg of wood and 640 Nm³ of air are supplied to the carbonization kiln, and 30 kg of tar and 1 981 Nm³ of non-condensable gas (off gas) are generated as by-products. Wood consists of woody part and ash, and is supplied to the kiln at 298 K. Air is fed at the same temperature as wood. The charcoal is discharged from the kiln at 313 K and contains 1.5 wt% of ash. Tar, non-condensable gas and condensed water vapor flow out from the kiln at 333 K. The non-condensable gas consists of CO, CO₂, H₂, H₂O and N₂. Its low calorific value is 6.55 MJ/m³, and can be exported to other processes outside the system after being separated from the water vapor and tar. Material balance revealed that about 150 kg of combustible materials is not recovered. Such materials are released to the environment as fume, dust or combustion gas. In this analysis, it is assumed that air encroaches into the kiln and burns completely the non-recovered materials, and combus-

| Table 1. Operation data of carbonization kiln. |
|-----------------------------------------------|
| **(a) Inflow**                                   |
| Material | Flow rate | Temperature |
|----------|-----------|-------------|
| Wood     | 1571 kg/thm | 298 K       |
| Combustion air | 640.0 Nm³/thm | 298 K     |
| Encroaching air | 546.0 Nm³/thm | 298 K    |
| **(b) Outflow**                                 |
| Material | Flow rate | Temperature |
|----------|-----------|-------------|
| Charcoal | 586.7 kg/thm | 298 K       |
| Tar      | 30.0 kg/thm  | 333 K       |
| Off gas  | 1981 Nm³/thm | 333 K      |
| Condensed water | 390.5 kg/thm | 333 K    |
| Leak gas | 708.5 Nm³/thm | 333 K    |
| **(a) Inflow**                                   |
| Material | Flow rate | Temperature |
|----------|-----------|-------------|
| Lump ore | 1459 kg/thm | 333 K       |
| Charcoal | 586.7 kg/thm | 298 K       |
| Limestone| 81.2 kg/thm  | 333 K       |
| Dolomite | 14.2 kg/thm  | 333 K       |
| Blast air | 1678 Nm³   | 973 K       |
| **(b) Outflow**                                 |
| Material | Flow rate | Temperature |
|----------|-----------|-------------|
| Hot metal | 1006 kg    | 1623 K      |
| Slag     | 148.0 kg   | 1673 K      |
| Top gas  | 2370 Nm³   | 378 K       |
| Dust     | 25.0 kg    | 378 K       |
| **(c) Compositions of solid and liquid materials (wt-%)** |
| Material | C | H | O | Ash |
|----------|---|---|---|-----|
| Wood     | 46.9 | 12.3 | 40.3 | 0.56 |
| Charcoal | 84.3 | 2.8 | 11.4 | 1.50 |
| Tar      | 56.8 | 7.3 | 35.9 | 0    |
| **(d) Compositions of gases (vol-%)**            |
| Material | CO | CO₂ | H₂ | H₂O | N₂ | O₂ |
|----------|----|-----|----|-----|----|----|
| Air      | 0.0 | 0.0 | 0.0 | 0.0 | 79.0 | 21.0 |
| Off gas  | 13.1 | 6.0 | 46.8 | 8.5 | 25.5 | 0.0 |
| Leak gas | 0.0 | 28.2 | 10.0 | 60.9 | 0.0 |

*: Flow rates and compositions of encroaching air and leak gas were determined from mass balance.

### 3. Exergy Analysis

Exergy analyses on the carbonization kiln and charcoal charged blast furnace were performed. Fundamentals of exergy analysis and details of implementation used in this study are reported by Akiyama and co-workers. The results of the analyses are discussed comparing with a conventional blast furnace ironmaking system.

Enthalpy and exergy balances of carbonization kiln are summarized in Table 3, and one of a reference coke oven are shown in Table 4. The enthalpy and exergy inputs to the carbonization kiln are respectively 35.0 and 31.7 GJ/thm, and are much larger than ones of coke oven. Most exergy inflow to the carbonization kiln is due to wood while exergy ratio of coal in coke oven is about 94%. Wood products are released to the atmosphere.

Table 2 shows a summary of mini blast furnace operation. The mini blast furnace uses 1 459 kg of rich small lump ore sized from 5 to 15 mm to produce a ton of hot metal. Limestone and dolomite are charged as flux materials, and their total amount is 95.4 kg/thm. Preheated air up to 973 K (blast gas) is injected into the furnace through tuyere at the rate of 1 678 Nm³/thm. Cold air is heated in an air-preheater of which fuel is part of the blast furnace off gas. Hot metal and slag are discharged at 1 623 and 1 673 K, respectively, and the slag rate is 148 kg/thm. Top gas that consists of CO, CO₂, H₂ and N₂ flows out from the furnace at 378 K, and its rate is 2 370 Nm³/thm. Forty percent of this gas is sent to air pre-heater as fuel to heat up blast gas, and the other portion is exported to other processes as energy source.

| Table 2. Operation data of charcoal charged blast furnace. |
|----------------------------------------------------------|
| **(a) Inflow**                                           |
| Material | Flow rate | Temperature |
|----------|-----------|-------------|
| Lump ore | 1459 kg/thm | 333 K       |
| Charcoal | 586.7 kg/thm | 298 K       |
| Limestone| 81.2 kg/thm  | 333 K       |
| Dolomite | 14.2 kg/thm  | 333 K       |
| Blast air | 1678 Nm³   | 973 K       |
| **(b) Outflow**                                          |
| Material | Flow rate | Temperature |
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| Slag     | 148.0 kg   | 1673 K      |
| Top gas  | 2370 Nm³   | 378 K       |
| Dust     | 25.0 kg    | 378 K       |
| **(c) Compositions of lump ore and molten slag (wt-%)**  |
| Material | Fe | Fe₂O₃ | SiO₂ | Al₂O₃ | CaO | MgO |
|----------|----|-------|------|-------|-----|-----|
| Ore      | 0.1 | 93.1  | 5.3  | 1.4   | --- | --- |
| Slag     | 1.0 | 44.6  | 16.0 | 35.7  | 2.5 |     |
| **(d) Compositions of additive matters (wt-%)**          |
| Material | CaCO₃ | Fe₂O₃ | Al₂O₃ | SiO₂ | FeO |
| Limestone | 94.4 | ---   | 2.5   | 1.1   | 0.9 |
| Dolomite | 57.3 | 41.6  | 0.4   | 0.4   | 0.3 |
| **(e) Composition of top gas (vol-%)**                    |
| Material | CO | CO₂ | H₂ | H₂O | N₂ | O₂ |
|----------|----|-----|----|-----|----|----|
| Top gas  | 17.8 | 18.7 | 46.6 | 3.1 | 55.9 | 0.0 |
| **(f) Composition of dust (wt-%)**                        |
| Material | C | Fe₂O₃ | Al₂O₃ | CaO | MgO | SiO₂ |
| Dust     | 30.0 | 57.2  | 0.5  | 6.0  | 0.5 | 3.0 |
itself works as fuel in the kiln, whereas the mixed gas of coke oven gas and blast furnace gas is fed to the coke oven separately from the coal. Although the calorific value of the wood is lower than coal, exergy and enthalpy inputs for unit mass production of charcoal are still larger because the raw material (wood) requirement of carbonization kiln is much larger than coke oven. Weight-basis yield of carbonization kiln is about 37 % while one of coke oven is about 70 %. Wood contains much moisture, and it thus requires heat of evaporation. Additionally, charcoal blast furnace system consumes about 40 % more weight of charcoal. These matters increase the enthalpy and exergy inputs to the system.

Outflow rate of exergy from the charcoal system are also larger than that of coke oven gas. The type of reference coke oven considered here is chamber oven, and its heat efficiency is generally excellent. Contrarily kiln usually has more external surface area concerning to the heat loss, thus it releases more heat to the atmosphere. The calorific value of off gas from the carbonization kiln is smaller than that of coke oven gas (COG) because it contains nitrogen and carbon dioxide. On the contrary, outflow rate of kiln off gas is about nine times larger than coke oven gas, and it raises exergy outflow and lowers exergy loss in carbonization process.

Table 3. Enthalpy and exergy balance of carbonization kiln.

| Material         | Flow rate | Enthalpy | Exergy |
|------------------|-----------|----------|--------|
| Wood             | 1571 kg   | 34977    | 31720  |
| Combustion air   | 640.0 Nm³ | 0.22     | 3.43   |
| Encroaching air  | 546.3 Nm³ | 0.19     | 2.93   |
| **Total**        |           | 34978    | 31726  |

Table 4. Exergy balance of coke oven.

(a) Inflow

| Material         | Flow rate | Exergy |
|------------------|-----------|--------|
| Coal             | 552 kg    | 17429  |
| Fuel gas**       | 341 kg    | 1168   |
| Combustion air   | 357 Nm³   | 2      |
| Electricity      |           | 7      |
| Pre-treatment    |           | 23     |
| **Total**        |           | 18692  |

(b) Outflow

| Material         | Flow rate | Exergy |
|------------------|-----------|--------|
| Coke             | 419 kg    | 12992  |
| COG              | 183 Nm³   | 2950   |
| Exhaust gas      | 582 Nm³   | 97     |
| By-products**    | 66 kg     | 2455   |
| **Total**        |           | 18104  |
| **Loss**         |           | 525    |

unit: [MJ/thm]

* Fuel gas consists of COG, BFG and LGD.
** By-products include tar, light oil, hydrocarbons, ammonia and hydrogen sulfide.

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An operation status of a reference blast furnace\textsuperscript{17,20,21} is summarized in Table 5. As mentioned above, the most remarkable differences in inflow materials to charcoal charged blast furnace compared with conventional system are use of small sized lump ore and charcoal. Total amounts of raw materials in both systems are almost same while the charcoal system uses 19 % more fuel as charcoal than conventional system. Furthermore, charcoal contains about 1.5 wt% of ash, thus the difference in inflow combustible matter becomes larger. The blast rate is also much higher (about 1.5 times), and no oxygen is enriched in charcoal system. Total lime (CaO) inflow into the conventional system is about 120 kg/thm while one in charcoal system is about 50 kg/thm. Regarding to the outflow materials from the blast furnace, slag generation in charcoal system is about a half of conventional system. On the contrary, top gas volume is about 1.4 times as conventional system. Gas utilization in charcoal system is 51.2 %, and one in conventional system is 50.9 %.

Enthalpy balance of both blast furnace processes are summarized in Table 6. Enthalpy inflow due to the fuel, namely charcoal, is higher than that of conventional system brought by coke and pulverized coal (14.9 GJ/thm). This higher enthalpy inflow is due to both higher calorific value of charcoal and larger fuel rate. On the other hand, temperature of hot blast in charcoal system is much lower than conventional one due to the utilization of 100 % lump ores that do not accept higher blast temperature. Thus its enthalpy value is lower than the blast of the conventional system al-

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| Material         | Flow rate | Exergy |
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| Fuel gas**       | 341 kg    | 1168   |
| Combustion air   | 357 Nm³   | 2      |
| Electricity      |           | 7      |
| Pre-treatment    |           | 23     |
| **Total**        |           | 18692  |

(b) Outflow

| Material         | Flow rate | Exergy |
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| Coke             | 419 kg    | 12992  |
| COG              | 183 Nm³   | 2950   |
| Exhaust gas      | 582 Nm³   | 97     |
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| **Total**        |           | 18104  |
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* Fuel gas consists of COG, BFG and LGD.
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Table 5. Operation data of reference blast furnace.

(a) Inflow

| Material       | Flow rate | Temperature |
|----------------|-----------|-------------|
| Raw materials  | 1612 kg/thm | 298 K       |
| Coke           | 383 kg/thm  | 298 K       |
| Pulverized coal| 110 kg/thm  | 298 K       |
| **Blaze**      | 1156 Nm³/thm| 1465 K      |

(b) Outflow

| Material         | Flow rate | Temperature |
|------------------|-----------|-------------|
| Hot metal        | 1000 kg/thm | 1796 K     |
| Slag             | 297 kg/thm  | 1604 K      |
| BFG              | 1739 Nm³/thm| 460 K      |
| Dust             | 5 kg/thm    | 460 K       |

(c) Compositions of iron bearing material and molten slag (wt-%)

| Material         | Fe₂O₃ | SiO₂ | Al₂O₃ | CaO | MgO   |
|------------------|-------|------|-------|-----|-------|
| Iron bearing     | 79.6  | 4.4  | 1.7   | 7.5 | 1.4   |
| Slag             | —     | 32.9 | 14.8  | 41.8| 6.2   |

(d) Composition of top gas (vol-%)

| Material | CO  | CO₂ | H₂ | H₂O | N₂   |
|----------|-----|-----|----|-----|------|
| Top gas  | 21.1| 21.9| 4.4| 4.1 | 48.5 |

An operation status of a reference blast furnace\textsuperscript{17,20,21} is summarized in Table 5. As mentioned above, the most remarkable differences in inflow materials to charcoal charged blast furnace compared with conventional system are use of small sized lump ore and charcoal. Total amounts of raw materials in both systems are almost same while the charcoal system uses 19 % more fuel as charcoal than conventional system. Furthermore, charcoal contains about 1.5 wt% of ash, thus the difference in inflow combustible matter becomes larger. The blast rate is also much higher (about 1.5 times), and no oxygen is enriched in charcoal system. Total lime (CaO) inflow into the conventional system is about 120 kg/thm while one in charcoal system is about 50 kg/thm. Regarding to the outflow materials from the blast furnace, slag generation in charcoal system is about a half of conventional system. On the contrary, top gas volume is about 1.4 times as conventional system. Gas utilization in charcoal system is 51.2 %, and one in conventional system is 50.9 %.

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| **Blaze**        | 1156 Nm³/thm | 1465 K |
| **Total**        |           | 34978    | 31726  |

unit: [MJ/thm]

* Fuel gas consists of COG, BFG and LGD.
** By-products include tar, light oil, hydrocarbons, ammonia and hydrogen sulfide.
though its rate is about 1.5 times larger. Total enthalpy input to the charcoal charged blast furnace is 18.8 GJ/thm and about 1.400 MJ/thm (about 7.4%) more than that of the conventional system, and this increase is mainly brought by the increase in enthalpy inflow due to charcoal. Regarding the outflow of enthalpy, slag generation in charcoal system is about a half of conventional one, and its temperature is 130 K lower. This causes that in enthalpy outflow due to the slag is less than a half of conventional one. On the contrary, although the temperature and calorific value of top gas in charcoal system is lower than conventional system, enthalpy outflow carried by the top gas is higher in charcoal system due to its larger flow rate.

Exergy balances for these two systems are shown in Table 7. Exergy inflow by the raw materials in charcoal system is lower than conventional one because the major material is unprocessed ore. The exergy inflows of fuels and blast gas show the similar tendency to enthalpy inflow. Exergy outflow of slag and top gas also follow the trend of enthalpy outflow. Total exergy input to the charcoal system is about 17.5 GJ/thm, and is 8.3% more than conventional system. Exergy outflow from the charcoal system is about 15.4 GJ/thm, and is also larger than that from the conventional system. Exergy loss in the conventional system shown in Table 7 is about 55% of one in charcoal system. However, if the unknown part is subtracted from the outflow exergy, the exergy loss of the conventional system comes close to the charcoal one. From these balances, although the charcoal charged blast furnace needs more enthalpy and exergy input to work, its efficiency is on comparable level with the conventional system.

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Figure 3 compares the exergy loss of the two ironmaking systems. The air heater in the biomass based blast furnace system is counter current heat exchanger called Glendon type. Stainless steel tubes are located inside a refractory brick chamber furnace in which the blast furnace gas is burned with air. The blast gas is heated during flowing inside these tubes. Since details of air heater in charcoal system are unavailable at present, operation of this process was determined from the following assumptions. Forty percent of the top gas that flows out from the blast furnace is sent to the air heater and is burned with the combustion air. The feed rate of the combustion air is set at air ratio of 1.05. The exhaust gas temperature is presumed 533 K. In the above conditions, ratio of blast furnace gas sent to the air heater and the temperature of the exhaust gas were given from the actual operating condition. Although the off-gas of the air heater is used for preheating of charged materials in the actual system, this process is not taken into account in this analysis. The exergy loss of sintering process was obtained based on the operating conditions listed in Table 8.15,18–20)

The exergy loss of charcoal ironmaking system is 4.53 GJ/thm while one of corresponding conventional system, which consists of coke oven, hot stove, sintering machine and blast furnace, is 4.29 GJ/thm. The charcoal system consumes about 6% more exergy in spite of exclusion of sintering process. Each process in the charcoal system shows larger exergy loss than corresponding process in conventional system, especially the air pre-heater consumes more than double as the hot stove in the conventional system does. This large exergy loss can be explained as follows. The blast flow rate in the charcoal charging blast furnace is much larger than that in conventional furnace, and thus the
air pre-heater needs more energy input. This raises the exergy inflow to the air pre-heater. On the other hand, the temperature of the hot blast heated in the air heater is lower than that of conventional system, hence the exergy outflow due to the hot blast is smaller in the biomass system. Consequently the exergy loss in the air pre-heater of charcoal system becomes larger. Although the charcoal charging system has constraint in the blast temperature as mentioned above, improvement of the air pre-heater efficiency is one of the key points to enhance system efficiency. Another reason for the larger exergy loss in each process is the size of the reactors. The charcoal charged blast furnace usually have the working volume up to 350 m³ while the conventional blast furnace that is used as the reference case in this study has inner volume of 5 151 m³. The outer surface area of the furnace per unit working volume increases with decrease in inner volume, thus smaller furnaces usually have larger heat loss. The heat loss gives rise to the exergy loss of the process, hence it is considered that each process shows larger exergy loss than corresponding process in conventional system. This analysis does not take into account the heat recovery by steam, and some other utilities. Although the heat recovery processes extract exergy available for the other processes from the wasted thermal stream, it is known that the exergy loss in the heat recovery from high temperature materials through sensible heat of lower temperature is considerably large. Thus the difference between these two processes could be smaller even when the exergy losses in utility processes in charcoal system were taken into account.

As mentioned above, one of the most remarkable features of the charcoal system is the reduction of the net carbon dioxide emission by the carbon recirculation. Its effect is summarized in Fig. 4 with comparison to the carbon dioxide emission from the conventional system.22) The carbon monoxide and the hydrocarbons in the COG and the BFG are counted as carbon dioxide because they are eventually converted into carbon dioxide through combustion in the other processes. Thus the carbon dioxide emission rate is shown as carbon rate. Noted that portions of the COG and the BFG are used as the fuels of the coke oven, the hot stove and the sintering processes the remaining parts of these gases are shown in this figure. Similar to the exergy loss, the carbonization kiln and the hot stove release more carbon dioxide as their exhaust gas than the coke oven and the hot stove in conventional system. The emissions of carbon dioxide as the exhaust gas directly from the charcoal and conventional systems are about 306 and 255 kg-C/thm, respectively, and the charcoal system release about 20% more carbon dioxide than conventional system. The difference between these two systems becomes larger when the carbon dioxide emission through the combustion of the COG and the BFG in the other processes. Charcoal system releases about 787 kg-C/thm of carbon dioxide while the conventional one emits about 528 kg-C/thm. Therefore the charcoal system generates carbon dioxide about 1.5 times as one from conventional system. About 737 kg of carbon, however, is brought into the charcoal system by the wood carbon, thus only about 50 kg-C/thm of the carbon dioxide is released to the environment. This remaining part of the carbon dioxide is mainly from the power generation process and the limestone feed.

These analyses revealed that the charcoal ironmaking system showed the comparable performance to the conventional system although the system analyzed here was in small scale and was supposed to have larger heat loss. Additionally the carbon dioxide emission from the charcoal system is much smaller than that from the conventional system. The ironmaking system with the charcoal charged blast furnace is expected to contribute environmental issues.

4. Conclusions

An exergy analysis on charcoal ironmaking system was...
performed and was compared with the conventional system. The results showed that the charcoal system needs more enthalpy and exergy inputs, whereas it produced more energy available in the other processes. Consequently the exergy loss in the system is in the comparable level with the conventional system. The analysis showed that each process included in the system still has possibility to be improved. Thus the performance of the charcoal system is expected to be equivalent to the conventional system. In addition, effective use of biomass resources, namely charcoal, reduces net emissions of carbon dioxide and sulfur dioxide to the atmosphere. Furthermore charcoal charged blast furnace generates less than a half slag of modern conventional blast furnace, and hot metal quality (ex. low sulfur content) is expected to improve. Although wood planting for charcoal system that produces equivalent amount of hot metal as even a modern blast furnace process needs vast land and long time (previous study\(^1\)) shows it needs 1 700 m\(^2\) and 7 years to grow eucalyptus trees for production of a ton of charcoal, thus about 25 500 square kilometers or 9 800 square miles of land is required for continuous production of 10 000 ton of hot metal every day, which is typical value of large scale blast furnace.) Although tree plantation technology has raised eucalyptus forest productivity about 20% in last two decades, there is no change in the necessity of the vast land, the charcoal charged blast furnace ironmaking system is expected to be one of the solutions to the environmental issues.

REFERENCES

1) K. Ishii and J. Yagi: *Tetsu-to-Hagané*, 87 (2001), 207.