Abstract
In order to reduce CO\textsubscript{2} generation in steel making processes, use of waste woods was proposed as a reducing agent of ironstones. A numerical model for gasification of waste wood chips was made to predict the gasification reaction. Experiments were also carried out and the validity of the model was verified. Based on the calculation results, the required thickness of the waste wood layer without discharge of ashes and charcoal was found out to be about 1m.

1 Introduction
Most of the waste woods produced from building or road construction sites have been burned after reuse so far. Those woods have, however, carbon sources as well as coal and oil, so that the use of the waste woods instead of coal or oil can reduce the CO\textsubscript{2} generation caused by the combustion of coal and oil. A lot of researches \cite{1}, \cite{2} to reuse the waste woods as energy resources have recently been carried out.

As for another application of waste woods besides the energy resources, the waste woods could be applied to iron-making processes. In the iron-making processes, coal is usually used for a reduction agent of ironstone. The coal, however, changes to CO\textsubscript{2} gas through some reactions in the iron-steel making process. A lot of CO\textsubscript{2} gas has been generated in iron-making processes for a long time. Nowadays, the amount of the generated CO\textsubscript{2} gas from iron and steel making processes reaches more than 10\% of the total amount in Japan. If some of the coal used in the iron-making processes is replaced by the waste woods, the CO\textsubscript{2} generation could be greatly reduced.

In order to use the waste woods in those applications, gasification characteristics of the waste woods should be clarified. There were some researches \cite{3}, \cite{4} to clarify the gasification characteristics of woods. However, those are for making energy gas and the studies on generating reduction gas in the iron-making process are very few.

In this study a useful and simple reaction model for design of gasification furnaces is proposed and its validity is verified by experiments. Based on the results from the model, discussions on both the reaction in the furnace and the required wood chip layer thickness are carried out. Gasification of waste woods is usually made as follows; the waste woods are dried by distillation to make charcoal and the charcoal is gasified by oxygen or air. Therefore, the present paper deals with the gasification of charcoal.

2 Reaction Model of Gasification

2.1 Reaction Considered
The following three reactions are considered.
\begin{align*}
C + O_2 &= CO_2 + 393.79\text{MJ/kmol}_{(O_2)} \\
C + CO_2 &= 2CO - 172.59\text{MJ/kmol}_{(CO_2)} \\
C + H_2O &= CO + H_2 - 131.39\text{MJ/kmol}_{(H_2O)}
\end{align*}

The reaction (3) occurs when water exists in the gas.
The reactions presented by equations (1) to (3) are assumed to occur on the surface of the wood chips. The reaction rates are usually dominated by both reaction rates at the reaction sites and mass transfer rates in the boundary films. Considering that the reactions occur on the wood chip surface, the temperature at the reaction sites would be high, e.g. around 1000K. In such case the reaction rates at the reaction sites would be higher than mass transfer rates in the films, thus reaction rates are considered to be under diffusion-controlled. In the present study the reactions presented by Eq. (1) to (3) are considered to be determined by the mass transfer rates.

2.2 Consumption Rates of Gases

It is assumed that the charcoal chips have cylindrical shape and only a charcoal chip exists in the gas. At first, the reaction presented by the Eq. (1) is considered.

The mass transfer coefficient in the boundary layer, diameter of a charcoal chip and mol fraction of oxygen in gas are denoted by $k_{o2}$, $dp$ and $C_{o2}$, respectively. Considering that thickness of the film is very small, the outer diameter of the film covering the charcoal is considered $dp$. The volume of oxygen gas passing through the film is expressed by $\pi dp H k_{o2}$. The charcoal length is denoted by $H$. The consumption rate of oxygen, $r_{o2}$ is expressed as the following equation.

$$r_{o2} = \pi dp H k_{o2} C_{o2}$$  \hspace{1cm} (4)

The volume and gas temperature in the film and the gas constant are denoted by $V_f$, $T_f$ and $R_u$, respectively.

$$p_{o2} V_f = n_{o2} R_u T_f$$  \hspace{1cm} (5)

then, mole fraction is

$$C_{o2} = \left( \frac{n_{o2}}{V_f} \right) = \frac{p_{o2}}{R_u T_f}$$  \hspace{1cm} (6)

Denoting pressure and volume fraction of oxygen as $p$ and $y_{o2}$, Eq. (6) is expressed as the following equation.

$$C_{o2} = \frac{py_{o2}}{R_u T_f}$$  \hspace{1cm} (7)

Considering that the film temperature is equal to the average of gas temperature outside the film, $T_g$, and the charcoal surface temperature, $T_c$, Eq. (7) is expressed as

$$C_{o2} = \frac{2py_{o2}}{R_u (T_g + T_c)}$$  \hspace{1cm} (8)

Substituting Eq. (8) for Eq. (4), Eq. (4) changes to the following equation.

$$r_{o2} = \pi dp H k_{o2} \frac{2py_{o2}}{R_u (T_g + T_c)}$$  \hspace{1cm} (9)

Denoting oxygen consumption rate per unit volume, the inner diameter of the furnace and number of the charcoal chips inside the furnace as $R_{o2}$, $D$ and $N$, respectively, Eq. (9) changes to

$$r_{o2} = \frac{8Ndpk_{o2}py_{o2}}{\pi D^2 \left( T_g + T_c \right)}$$  \hspace{1cm} (10)

The consumption rates of carbon-dioxide and steam, $R_{CO2}$ and $R_{H2O}$ are expressed as follows;

$$R_{CO2} = \frac{8Ndpk_{CO2}py_{CO2}}{D^2 R_u \left( T_g + T_c \right)}$$  \hspace{1cm} (11)

$$R_{H2O} = \frac{8Ndpk_{H2O}py_{H2O}}{D^2 R_u \left( T_g + T_c \right)}$$  \hspace{1cm} (12)

2.3 Gas Flow Rates

When the reactions presented by Eq. (2) and (3) occur, gas flow rate varies toward the flow direction. Considering the volume per unit cross sectional area with the height of $dx$, the mole number of the gas generated in the volume per unit time is expressed as follows;

$$(R_{CO2} + R_{H2O}) dx$$  \hspace{1cm} (13)

Denoting the gas flow rate under normal condition as $F$, the variation of the gas flow rate is expressed as
\[
\frac{dF}{dx} = 22.4(R_{CO2} + R_{H2O}) \quad (14)
\]

2.4 Distribution of Gas Components

The volume fractions of oxygen, carbon-dioxide, carbon-oxide, steam and hydrogen are denoted by \(y_{O2}, y_{CO2}, y_{CO}, y_{H2O}, y_{H2}\). At first, oxygen is focused on. The oxygen volume flux, gas flow rate per unit time and unit cross sectional area, is \(F_{yO2}\). The streamwise gradient of the oxygen volume flux expressed as the following equation.

\[
\frac{d(F_{yO2})}{dx} = -22.4R_{O2} \quad (15)
\]

Substituting Eq. (14) for Eq. (15),

\[
\frac{dy_{O2}}{dx} = \frac{22.4}{F}\left\{ R_{O2} - y_{O2}(R_{CO2} + R_{H2O}) \right\} \quad (16)
\]

The volume fraction gradients of the other components are presented as follows;

\[
\frac{dy_{CO2}}{dx} = \frac{22.4}{F}\left\{ R_{O2} - (1 + y_{CO2})R_{CO2} - y_{CO2}R_{H2O} \right\} \quad (17)
\]

\[
\frac{dy_{CO}}{dx} = \frac{22.4}{F}\left\{ (2 - y_{CO})R_{CO2} + (1 - y_{CO})R_{H2O} \right\} \quad (18)
\]

\[
\frac{dy_{H2O}}{dx} = \frac{22.4}{F}\left\{ y_{H2O}R_{CO2} - (1 + y_{H2O})R_{H2O} \right\} \quad (19)
\]

\[
\frac{dy_{H2}}{dx} = \frac{22.4}{F}\left\{ y_{H2}R_{CO2} + (1 - y_{H2})R_{H2O} \right\} \quad (20)
\]

2.4 Gas Temperature

Consider the heat balance in unit volume and unit time. The input heats are considered as follows;

(1) Input Heat
a. Heat from upstream
   It is expressed as \(\rho_g F c_g T_g\).
b. Reaction Heat

The reaction heats of the reactions (1) to (3) are expressed as follows;

\(393790R_{O2} - 172590R_{CO2} - 131390R_{H2O}\)

C. Sensible heat when charcoal changes to gas

\[(R_{O2} + R_{CO2} + R_{H2O})M_c c_e T_e\]

(2) Output Heat
a. Heat to downstream

It is expressed as \(\rho_g F c_g T_g + d(\rho_g F c_g T_g)\)

Using the heats presented above, gas temperature gradient in the furnace is expressed as the following equation.

\[
\frac{dT_g}{dx} = \frac{1}{\rho_g c_g F}\left\{ -\rho_g c_g T_g \frac{dF}{dx} + 393790R_{O2} - 172590R_{CO2} - 131390R_{H2O}
\]

\[+(R_{O2} + R_{CO2} + R_{H2O})M_c c_e T_e \right\} \quad (21)
\]

The streamwise distributions of the gas temperature and gas compositions are able to be calculated from Eqs. (16) - (20) and (21).

3. Experimental

3.1 Experimental Setup

Figure 1 shows the schematic diagram of the gasification furnace. The furnace was 97mm in inner diameter and 452mm in total length. The charcoal chips were inserted into the furnace and the air was blown from the bottom of the furnace. An entrance section of 200 mm depth was built to regulate the air flow and make the air velocity across the cross section uniform. The charcoal chips were supported by the steel wire netting mounted between the gasification furnace and the entrance section. Since ashes dropped through the wire netting, the surfaces of the charcoal chips were kept fresh.

Five K-type thermocouples were fitted up with a gap of 65mm toward the streamwise direction. The data of the temperatures were sampled at a interval of 1 second. To prevent heat losses from the furnace, the furnaces were covered with the insulator on the outer surface.
Since the heat capacity of the furnace is large, the furnace was pre-heated before experiments using a pre-heater connected to the furnace serially.

The charcoal chips employed in the present study were 30mm in outer diameter and 150mm in length. The charcoal chips were inserted into two layers in the furnace. The experiments were made under atmospheric pressure and air velocities, \( F_i \), are 0.45, 0.675, 0.90, 1.125, 1.350 and 1.575 Nm/s.

### 3.2 Experimental Results

Figure 2 shows the temperature variations measured at 5 streamwise locations. The symbol of 0 in the figure shows the time when air began to be blown into the furnace. From the figure the gas temperatures began to rise as soon as the air was blown. The gas temperature \( T_2 \) reaches nearly constant value around 200 second and \( T_3 \) to \( T_5 \) do so around 400 second. After taking nearly constant, the gas temperatures decrease with time. This could be caused by the reason that the amount of ashes increased and it brought the decrease of both reaction sites and reaction heat.

In the present analysis the reaction is considered to occur on whole surface area of the charcoal chips, so that the data without any effects of ashes must be required to verify the validity of the proposed reaction model. In the condition shown in Fig. 2, the data at 400 second were employed.

### 3.3 Verification of Analytical Data

Figure 3 shows the comparison between the measured and calculated gas temperature distributions. The measured data in Fig. 3 were those at 400 second in Fig. 2. The symbol, \( L \), shows the distance from the bottom of the furnace, at which the steel wire netting was mounted. Figure 3 shows that the measured data and the calculation are well consistent, thus the reaction model could be considered valid.
4. Gas Composition and Furnace Depth

4.1 Streamwise Variation of Gas Temperature and Composition.

Figure 4(a) and 4(b) show the streamwise distribution of the gas temperature and the gas compositions of $O_2$, $CO$ and $CO_2$. In every condition, the oxygen volumetric fraction decreases with the distance from the bottom of the furnace, $L$. The volumetric fraction of $CO_2$ is larger than that of $CO$ in the region of small $L$, while that of $CO$ becomes larger in larger $L$ region. That is caused by the reason that $CO$ gas is generated from $CO_2$ gas.

Focusing on the gas temperature, the temperature rising, having a maximum value, then decreases in both cases. However, the length at the temperature having a maximum value is about 0.15m for case (a) and about 0.25m for case (b), thus higher the air velocity is, longer the distance for the gas temperature being maximal is. Furthermore, the temperature at the gas temperature being maximal in larger air velocity is higher than that in smaller air velocity.

The reaction in Eq. (1) is an exothermic reaction, while the reaction in Eq. (2) is an endothermic reaction. Considering the reaction from the gas composition distribution shown in Fig. 4(a) and (b), the exothermic reaction expressed by Eq. (1) is major around the bottom of the furnace, while the endothermic reaction expressed by Eq. (2) is major in the wide region except for bottom region. It could be caused by the change of the major reaction that the gas temperature has a maximum value.

The distance between the bottom of the furnace and the location of the gas temperature being maximal is named Oxidization layer and is denoted by $L_o$.

In comparison of $CO$ gas volume fraction between the conditions of (a) and (b), the length for completion of the reaction gets longer with increase of air velocity. In the condition of Fig. 4(b), higher air velocity condition, $CO$ gas generation is not completed at the end of the furnace.

4.2 Required Height of Gas Furnace

The output gas of high $CO$, low $O_2$ and $CO_2$ volumetric fractions is required for good
gasification furnaces. So, the required condition for generating gas of high CO fraction is discussed from the calculated results. The zone length from the bottom of the furnace to the location where the following condition is achieved is named reaction layer thickness and denoted by \( L_r \).

\[
\frac{y_{CO}}{(y_{CO} + y_{CO_2})} = 0.99
\]  

The determined oxidization and reaction layers are shown in Fig. 5. Figure 5 reveals that those layers become thick with increase of air velocity. In the present study the oxidization layer thickness is 0.1 – 0.3 m and the reaction layer thickness is about 5 times as long as the oxidization layer thickness.

Some ashes and charcoal dusts came out from the outlet of the furnace when the air velocity is over 1 m/s. If furnaces require operations of no dust, the air velocity must be under 1 m/s. In this case the reaction layer thickness is about 1 m. Therefore, it can be decided that the required furnace height is 1 m.

5. Concluding Remarks

Numerical calculation and experiments were carried out and the following findings are revealed.

1. A gasification model for waste woods was proposed. In comparison between calculated and measured data, the gasification model was verified its validity.

2. In the present study the oxidization layer thickness was 0.1 – 0.3 m and the reaction layer thickness is about 5 times as long as the oxidization layer thickness.

3. The air velocity should be under 1 m/s in order not to come out ashes and charcoal dusts from the furnace. In this case the minimum height of the furnace is about 1 m.

Acknowledgement

This research was supported by grant-in-aid for exploratory research and we’d like to express our thanks to the ministry of education, culture, sport, science and technology.

References


