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# NUMERICAL ANALYSIS ON BLAST FURNACE PERFORMANCE BY MULTI-DIMENSIONAL TRANSIENT SIMULATOR BASED ON MULTI-FLUID THEORY

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## ABSTRACT

A mathematical model has been developed for simulating the blast furnace operation with carbon composite agglomerates charging based on multi-fluid theory and reaction kinetics. In this model, the behaviors of carbon composite agglomerates are considered based on previously reported experimental research, and conservation equations and chemical reactions of carbon composite agglomerates are newly introduced. A series of calculations are performed to examine the effect of charging carbon composite agglomerates. The model calculation gives two-dimensional distributions of process variables and information on the overall operational parameters. It reveals that in-furnace temperature levels significantly decrease and the reduction of carbon composite agglomerates is retarded with carbon composite agglomerates charging ratio. The furnace performance is remarkably improved with the increase in carbon composite agglomerates rate. The productivity tends to increase while coke rate and total reducing agent rate show decreases at the different degree.

**KEY WORDS**: carbon composite agglomerates, blast furnace, mathematical model, multi-fluid theory.

## INTRODUCTION

The blast furnace is a principal unit in the ironmaking process and regarded as one of the most complex counter current metallurgical reactor in the chemical engineering field since numerous species are interacting and a large number of physical and chemical phenomena are involved. It is difficult to measure in-furnace phenomena in detail, thus a mathematical model of the furnace is a useful tool for understanding, controlling and improving blast furnace performance, especially in applications of new technologies, such as high rate of fine coal injection and the reuse of ferrous and carbonaceous wastes. The authors have developed a multi-dimensional transient mathematical simulator of the blast furnace operation (Castro, Nogami and Yagi, 2000). In this study, the mathematical model has been modified and applied to examine an innovative blast furnace operation.

From the viewpoints of process optimization, energy saving, resource recycling and environmental protection, carbon composite agglomerates have been drawing much attention as new raw materials for ironmaking. The carbon composite agglomerates are the mixtures of fine iron ore (hematite, magnetite, iron-bearing ironmaking dust and pre-reduced iron ore fine) and fine carbonaceous materials (fine coke, fine coal, charcoal and char) adding some amount of binding agents in most cases. Compositions, shape, carbon content and physical properties of agglomerates vary in a wide range corresponding to raw materials and process conditions. In the past, carbon-bearing agglomerates were mainly adopted in some established or partly industrialized rotary hearth processes, such as FASTMET, INMETCO and COMET, in which advantages like comparatively faster reduction rate and lower fuel rate had been reported. Recently, application of carbon composite agglomerates into blast furnace and electric furnace processes has been attracting technical and scientific interest.

A large number of fundamental research have been carried out for various carbon agglomerates, these focusing mainly on reduction and melting behaviors (Meng, et al, 2001; Zhang, et al, 1995), carburization mechanism (Matsumura, et al, 1999), effect of surrounding gas atmosphere (Ueki, et al, 2001) and carbon content (Matsumura, et al, 1999) on reduction rate Furthermore, carbon-bearing agglomerates were tested in some practical blast furnaces and a blast furnace simulator called "BIS" (Kono, et al, 2000) and it revealed that: 1) Carbon composite agglomerates charging had no deleterious effects on gas penetration, burden descending and smooth running; 2) Reduction of iron ore in the agglomerates started from lower temperature zone and completed much faster compared with sinter or pellet; 3) Energy consumption tended to decrease significantly.

Generally, the following advantages are expected by feeding carbon composite agglomerates into blast furnace including: 1) Less sinter and coke products are needed thus decreasing energy consumption and environmental load; 2) The effective use of non-coking coal, and iron-bearing dust and sludge in steel works enlarges the range of raw materials and promotes resource recycling; 3) Fine iron ore and carbonaceous materials are mixed with micron scale in the agglomerates. Hence, a fast reduction reaction is expected. Furthermore, carbon gasification and iron ore reduction reactions are mutually accelerated and occur at lower temperature due to the coupling effect. As a result, charging carbon composite agglomerates to blast furnace is expected to improve process performance and decrease energy consumption.

Regarding the method of agglomeration, it is reported that common cold-bonded carbon agglomerates have poor strength, especially during reduction, which is one restriction for blast furnace to accommodate large amount of agglomerates input. A hot briquetting process was proposed to manufacture carbon composite iron ore briquette (hereinafter abbreviated as CCB) from the mixture of fine coal and fine iron ore (Kasai, et al, 2001). Compared with the other carbon containing agglomerates, this briquette shows better reducing performance, lower cost and higher strength due to thermal plasticity of coal.

Although this briquette was experimentally tested in the blast furnace simulator "BIS", theoretical evaluation has yet to be made. In this study, the effect of charging carbon composite agglomerates on blast furnace operation, including the variation of process variables distribution and operational parameters, is numerically investigated.

## MATHEMATICAL MODEL

### Fundamental Framework

In this study, the above mentioned multi-fluid blast furnace model is modified to simulate blast furnace operation with charging CCB. The mathematical model is two-dimensional, axisymmetric and steady state. The calculation domain is from the slag surface in the hearth up to the burden surface in the throat, namely the packed bed region of blast furnace. This simulator uses multi-fluid theory and handles gas, solid (coke, iron-bearing burdens), hot metal, molten slag and fine powders (pulverized coal) as separate phases having individual flow mechanisms. Each phase consists of one or more components and each component has its own composition and physical properties. Due to mutual interactions, all phases are considered simultaneously, giving a large set of strongly coupled governing equations. The governing conservation equations for all phases can be expressed by a single generalized form.

$$\frac{\partial}{\partial x}(\varepsilon_i \rho_i u_i \psi) + \frac{1}{r}\frac{\partial}{\partial r}(r\varepsilon_i \rho_i v_i \psi) = \frac{\partial}{\partial x}(\varepsilon_i \Gamma_\psi \frac{\partial \zeta}{\partial x}) + \frac{1}{r}\frac{\partial}{\partial r}(r\varepsilon_i \Gamma_\psi \frac{\partial \zeta}{\partial r}) + S_\psi \quad (1)$$

The variable $\psi$ represents the variables to be solved. By changing $\psi$, this general equation represents the conservation of mass, momentum, enthalpy and chemical species for each phase $i$ considered in the model. $\Gamma_\psi$ is the effective diffusive transfer coefficient, which assumes a different meaning for each dependent variable to be solved. Additionally, $S_\psi$ is the source term, which occurs due to chemical reactions, interaction, external forces and phase changes, etc. For the conservation of mass, momentum and chemical species, $\zeta$ takes the same dependent variable as $\psi$. But for enthalpy conservation, $\psi = H_i$ while $\zeta = T_i$, and the conductive heat transfer terms become source term. The details of this model framework have been described in previously published reports (Austin, et al, 1997; Nogami, 2003).

The blast furnace operation examined in this study is with CCB charging onto burden surface. Therefore, the agglomerate is treated as one component of solid phase. The solid phase consists of three components namely sinter, coke and CCB. Bulk solid properties, such as diameter, porosity and specific surface area, are calculated as the average of the component properties based on the component volume fractions. Regarding the chemical species, even the same species, for example carbon in coke and carbon in CCB, these are treated separately because they participate in different reaction schemes. Therefore, conservation equations of CCB species are newly introduced into the model and they include chemical reactions and phase changes in which these species participate.

All conservation equations are solved simultaneously. The furnace is represented by a numerical grid of body-fitted coordinate type, and the governing conservation equations are discretized over the numerical grid using the control volume method. The SIMPLE scheme and iterative matrix methods are used to solve the equations.

### Reactions of CCB in Blast Furnace

In this study, it is assumed that the CCB consists of hematite, carbon and gangue ($SiO_2$, CaO, MgO and $Al_2O_3$). The behavior of CCB in a blast furnace is described as follows. After CCB is charged into blast furnace, it is heated up through heat transfer from ascending gas. When the temperature reaches a certain level, the reduction of iron oxide by solid carbon occurs inside the CCB. By this reaction, CO and $CO_2$ are simultaneously released as gaseous products. Furthermore, solution loss reaction between carbon at the CCB surface and $CO_2$ in gas stream is considered. When CCB continues to descend and enters high temperature zone, softening and melting of reduced iron, iron oxide (if still present) and gangue in CCB occur. Note that, the melting of iron oxide takes place when the total reduction degree of CCB reaches 0.33, and melted iron oxide transfers into the slag phase. The carburization of CCB is also considered in the model. Finally, excess carbon is consumed through raceway combustions.

Actual CCB reduction includes simultaneous iron oxide reduction and carbon gasification. They, however, are difficult to be separated. To formulate the reduction behavior of CCB the following assumptions are made: 1) Carbon reduction is expressed by the following formula $\beta FeO_x + C = \beta FeO_{(x-\frac{2-\alpha}{\beta})} + \alpha CO + (1-\alpha)CO_2$ ; 2) In a CCB particle, the composition, temperature and physical properties are uniform and carbon reduction reaction occurs uniformly; 3) From the previous study (Zhang, et al, 1995), gaseous products of CCB reduction have an equilibrium composition with wustite reduction; 4) Reduction rate of CCB is not affected by surrounding gas compositions.

The total reduction of CCB is summarized by the following formula.

$$2FeO_x + C = 2FeO_{(x-\frac{1+2K}{2+2K})} + \frac{1}{1+K}CO + \frac{K}{1+K}CO_2 \quad (2)$$

Noted that, $K$ is reaction equilibrium constant for wustite reduction by CO, viz $Fe_wO + CO = wFe + CO_2$, which is dependent on the local solid temperature.

The reaction rate of CCB carbon reduction is calculated by the following equation.

$$R = kC_{CCB} \quad (3)$$

Where $k$ is reaction rate constant and $C_{CCB}$ is residual carbon amount in the CCB. It is reported that reaction rate constant shows different value depending on temperature $T$ and the gasification ratio $F_c$. The model selects the rate constant (Ueki, et al, 2001) by comparing $F_c$ and the critical value $F_c^*$, described as follows.

$$k = \begin{cases} \exp(5.51 - 130000/RT) & (F_c \le F_c^*) \\ \exp(5.67 - 160000/RT) & (F_c > F_c^*) \end{cases} \quad (4)$$

$$F_c^* = 1 - \exp(7.598 - 0.00655T) \quad (5)$$

### Evaluation Procedure

To evaluate the operational performance of the blast furnace with CCB charging, the calculating conditions were determined as follows. The blast furnace operation without CCB charging is first simulated as a base case. As a result of this computation, hot metal temperature is obtained and this temperature is recorded as the reference hot metal temperature. In the simulation for CCB charging, ratio of coke to iron-bearing components (sinter+CCB) in charged materials is adjusted to reproduce the reference hot metal temperature. This ratio is determined through trial-and-error method, while the ratio of CCB to sinter is kept constant. A temperature difference from the reference value less than 5 K is accepted. For all cases tested, blast conditions and pulverized coal injection conditions are kept constant. The model calculation gives the two-dimensional distributions of process variables and the main information for operational parameters. By comparing these results in different cases, the variation of the furnace performance is clearly shown.

## RESULTS AND DISCUSSION

### Calculating Conditions

Simulations were performed for a blast furnace with diameter 11.2 m, height 25.2 m and effective inner volume 2303 $m^3$. The primary operating conditions for blast and pulverized coal injection are listed in **Table 1**.

| Item | Value |
|---|---|
| Blast temperature [$^oC$] | 1050 |
| Blast rate [$Nm^3$/min] | 4119 |
| Oxygen enrichment [mol %] | 3.0 |
| Blast humidity [g-$H_2O/Nm^3$] | 2.3 |
| PC injecting rate [kg/s] | 8.0 |
| Raceway temperature [$^oC$] | 2124 |
| Bosh gas flow rate [kmol/s] | 3.998 |

**Table 1**: Main operation conditions used in this study.

(Unit: mass %)

| $Fe_2O_3$ | $Fe_3O_4$ | FeO | Fe | $H_2O$ | C | Gangue |
|---|---|---|---|---|---|---|
| 75 | 0 | 0 | 0 | 0 | 20 | 5 |

**Table 2**: The composition of CCB used in this model.

| Item | Sinter | CCB |
|---|---|---|
| $T_{Fe}$ [mass %] | 59.4 | 52.7 |
| Inlet temperature [$^oC$] | 25 | 25 |
| Density [$kg/m^3$] | 3500 | 4200 |
| Shape factor [-] | 0.84 | 0.95 |
| Diameter [mm] | 16-30 | 15 |

**Table 3**: Physical properties of sinter and CCB.

Furthermore, inflow conditions for blast and pulverized coal are used as boundary conditions at the tuyere inlet. Solid temperature, composition and distributions of component volume fraction, etc are specified as boundary conditions at the burden surface in the model. The composition of CCB and physical properties of CCB and sinter are listed in **Table 2** and **3**. This study investigated four different cases, in which the mass percentage of CCB in iron-bearing burdens (sinter and CCB) is 0, 10, 20 and 30 and the first one is set as base case. Volume fraction distributions of solid components on the burden surface for each case are shown in **Fig. 1**. The CCB is charged across the whole radius and the volume fraction of sinter and CCB is comparatively lower in the center than that in the other regions.

Note that the reference hot metal temperature of 1560 $^oC$ is an average over the slag surface.

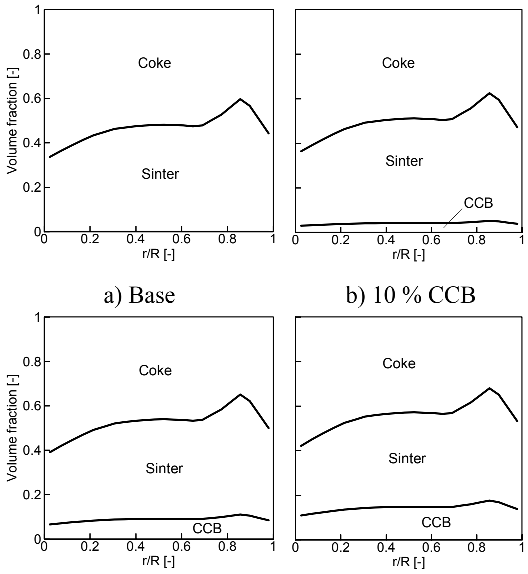



**Figure 1**: Charging patterns of solid components used in this study.

### Distributions of Process Variables

In this section, the effect of CCB charging ratio is discussed based on in-furnace distribution of process variables. The two-dimensional distributions of process variables come from the solution of the governing conservation equations.

Solid temperature is implicitly defined by the solid enthalpy and composition (Austin, et al, 1997). **Fig. 2** shows predicted solid temperature distributions for different CCB charging ratios. In the following figures, the cohesive zone is defined by solid temperature from 1200 to 1400 $^oC$ (indicated by dashed lines) while the shapes of deadman and raceway are represented by thick solid curves. The calculation results reveal that isotherms are gradually shifted downward with increase in CCB charging ratio and the region between 800 and 1200 $^oC$ isotherms becomes narrow. The location of cohesive zone also tends to descend with the increase in CCB charging ratio. This variation of furnace temperature is clearly described in the distribution of averaged solid temperature along furnace height, as shown in **Fig. 3**. Solid temperature increases with decrease in height. From the middle to upper part of the furnace region, a gentle temperature gradient is formed. It is referred to as thermal reserve zone. The temperature of the thermal reserve zone decreases with the increase in CCB charging ratio. For 30 % CCB case it decreases by over 200 $^oC$ compared with base case.

**Figure 4** shows change in distribution of CCB reduction degree with CCB charging ratio. **Fig. 5** describes the distribution of averaged reduction degree of CCB and sinter along furnace height. The reduction of CCB starts at about 700 $^{o}$C, contour of 10 % corresponds to isotherm of 800 $^{o}$C. The reduction of CCB is retarded with the increase in CCB charging ratio, which is clearly seen in **Fig. 5 (a)**. At the same height the reduction degree of CCB is decreased. Regarding sinter reduction degree, the reduction of hematite mainly occurs in the upper shaft and CCB charging ratio has little effect on this reduction step. In contrast, reduction stages of magnetite and wustite show a delay with the increase in CCB charging ratio. The effect, however, is less than that on CCB reduction.

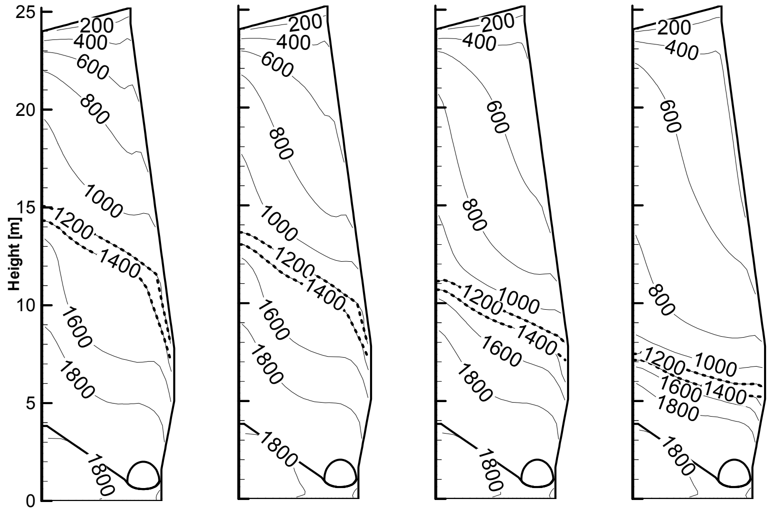



**Figure 2**: Effect of CCB charging ratio on distribution of solid temperature [unit: $^{o}$C].

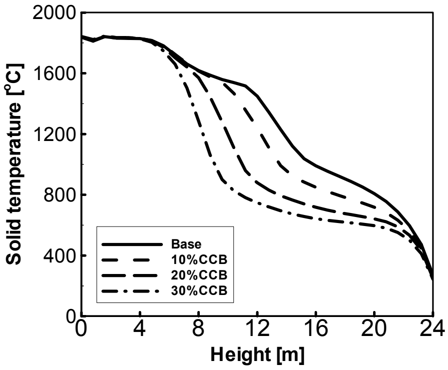



**Figure 3**: Distribution of averaged solid temperature along furnace height.

#### Variations of Operational Parameters

**Figure 6** shows the effect of CCB charging ratio on productivity, slag rate, reducing agent consumption including pulverized coal, coke and carbon in CCB, top gas temperature and utilization degree of top gas carbon monoxide.

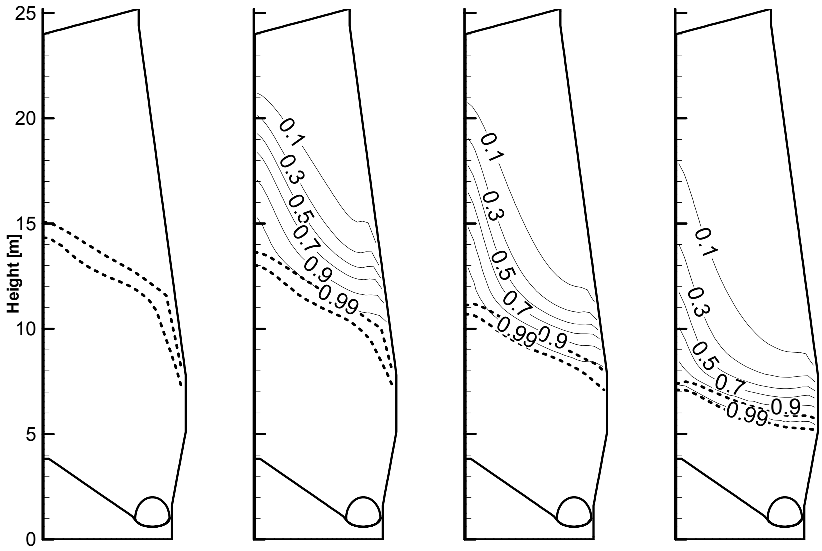
The productivity shows obvious increase with the CCB charging ratio while slag rate tends to decrease. If the ratio of CCB in iron-bearing burdens increases from 0 to 30 %, the hot metal productivity is improved by 12.0 %, and the predicted slag rate is lowered by 15.4 %.

With the increase in CCB ratio, the carbon brought into the furnace by CCB is proportionally increased. Pulverized coal rate [kg/thm] shows a little decrease due to the increase in hot metal productivity while pulverized coal injection rate [kg/s] is constant for each case. Coke rate shows remarkable decrease and it is lowered by about 3.9 kg/thm corresponding to the increase of CCB mass ratio in iron-bearing burdens by 1 %. Total reducing agent rate (RAR) including the carbon in CCB is reduced by about 6.3 % corresponding to the CCB ratio increasing from 0 % to 30 %.

Finally, both top gas temperature and CO efficiency decrease with CCB charging ratio.

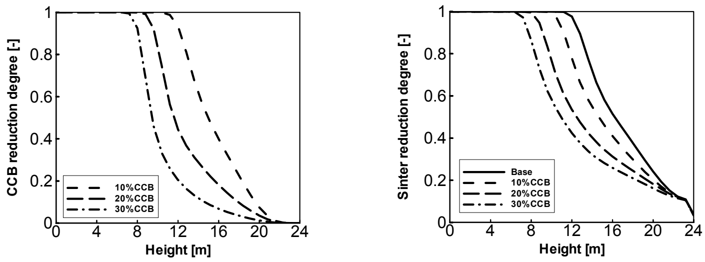
#### Analysis of Heat Balance

In this section, heat balance of the blast furnace is analyzed. Based on this, the mechanisms for the variation of process variables distribution and operation parameters are discussed.



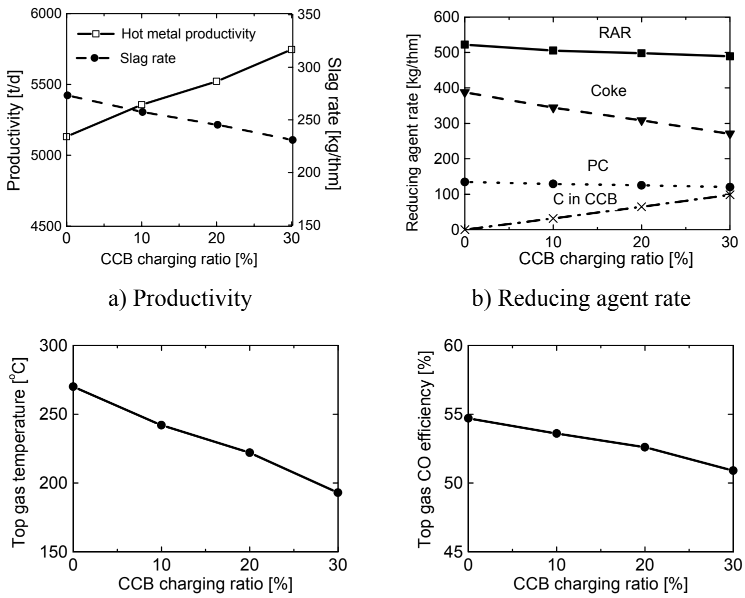

a) Base b) 10% CCB c) 20% CCB d) 30% CCB

**Figure 4**: Effect of CCB charging ratio on distribution of CCB reduction degree [unit: -].




a) CCB b) Sinter

**Figure 5**: Distribution of averaged reduction degree along furnace height.




a) Productivity b) Reducing agent rate

c) Top gas temperature d) Top gas CO efficiency

**Figure 6**: Predicted operational parameters under different charging rate of CCB.

| Item | | Base | 10%CCB | 20%CCB | 30%CCB |
|---|---|---|---|---|---|
| In | Blast | 100.3 | 100.3 | 100.3 | 100.3 |
| | Raceway combustion | 185.8 | 185.8 | 185.8 | 185.8 |
| | Others | 12.3 | 12.3 | 12.3 | 12.3 |
| | Total | 298.4 | 298.4 | 298.4 | 298.4 |
| Out | Top gas | 35.5 | 31.5 | 28.8 | 24.7 |
| | Hot metal | 58.2 | 60.8 | 62.7 | 65.6 |
| | Hot slag | 35.1 | 34.5 | 33.8 | 33.1 |
| | Heat loss through wall | 19.0 | 17.8 | 16.0 | 13.4 |
| | Reduction and melting of CCB | 0.0 | 20.2 | 42.1 | 66.4 |
| | Reduction and melting of sinter | 43.5 | 41.6 | 38.3 | 35.1 |
| | Direct reduction | 13.7 | 13.1 | 12.8 | 11.6 |
| | Solution loss reaction | 64.7 | 59.0 | 52.6 | 44.9 |
| | Silicon transfer reactions | 10.7 | 9.2 | 6.9 | 4.2 |
| | Others | 17.7 | 10.5 | 4.6 | 1.6 |
| | Total | 298.1 | 298.2 | 298.6 | 300.6 |
| Solid charging rate [kg/s] | | 116.2 | 113.2 | 122.8 | 127.0 |
| (Sinter+CCB)/coke [-] (mass ratio) | | 4.050 | 4.342 | 5.234 | 6.056 |

**Table 4**: Heat balance of blast furnace for each case studied [unit: MJ/s].

Heat balance of the blast furnace is summarized in **Table 4**. Heat input mainly consists of sensible heat of in-flowing raw materials (blast, pulverized coal and solid burdens) and combustion heat of carbonaceous materials in raceway. While heat output consists of sensible heat taken away by top gas, hot metal and slag, wall heat loss and heat demands for all the other in-furnace reactions except combustion. Reactions demanding heat include indirect reduction and melting of sinter, carbon reduction and melting of CCB, direct reduction in the slag, solution loss, water gas reaction, gangue melting, carburization and silicon transfer reactions, etc.

Total heat input is almost the same due to constant raceway conditions for all the cases. Regarding heat consumption, heat requirement for CCB reduction and melting increases with CCB charging ratio while heat demand for reduction and melting of sinter decreases. With the increase in the CCB charging ratio to 10 %, 20 % and 30 %, the necessary heat for CCB reduction and melting is increased by 20.2, 42.1 and 66.4 MJ/s, correspondingly, while heat consumption for sinter reduction and melting is decreased by 1.9, 5.2 and 8.4 MJ/s. The CCB demands more heat than sinter. Thus, the heat requirement for reduction and melting of iron bearing burdens increases with the CCB charging ratio. In contrast, the heat demands for solution loss and silicon transfer reactions, heat outflow by top gas and wall heat loss tend to decrease with the CCB charging ratio, which is major difference for CCB charging operation. The reduction of heat demands compensates the increased heat requirement by the CCB reduction. As a result, the furnace efficiency improves despite the delay of the reduction of iron bearing materials and the increase in burdens charging rate with CCB charging ratio. The energy consumption is lowered.

According to model computation results, mass ratio of iron bearing burdens (sinter and CCB) to coke increases from 4.050 to 6.056 with the response to CCB charging ratio increased from 0 to 30 %. The increase in charging rate of iron bearing burdens with CCB charging ratio contributes to the improvement of productivity and decrease of coke rate. In addition, less gangue inflow from coke (lower coke rate) and CCB (lower gangue content) reduces slag discharge.

In the case with CCB charging evaluated in this study, the reaction of CCB carbon reduction show sudden increase in the belly zone, which consumes a large amount of heat. With the increase in CCB charging ratio, more heat is needed in belly and available heat for the upper zone tends to decrease. As a result, top gas temperature lowers. On the other hand, utilization degree of top gas carbon monoxide is mainly dependent on the reduction of sinter and CCB. In the base case (without CCB charging), CO efficiency is about 54.9 %. However, the typical ratio of $CO_2$ to CO for CCB carbon reduction given by the equilibrium is about 0.445 (at 1000 °C), corresponding to a lower CO utilization degree of 31 %. Thus, top gas CO efficiency decreases with CCB charging ratio.

As mentioned above, in-furnace solid temperature decreases with CCB charging ratio. Under the premise that heat input is kept constant, lower in-furnace temperature levels are shown for the case with higher CCB input; this is due to the following two factors: 1) the heat demand for CCB carbon reduction is drastically increased, and 2) the charging rate of solid burdens is increased. For the four cases studied, the calculated charging rate of solid burdens is 116, 120, 123 and 127 kg/s respectively. Evidently, heat demands of solid, both sensible and latent heat, are increased. The decrease in furnace temperature retards the reduction of CCB and sinter.

## CONCLUSIONS

Carbon composite iron ore briquette (CCB), one of the high-quality carbon composite agglomerates, has been examined as a raw material for blast furnace ironmaking. In the study, a multi-fluid blast furnace model is developed to numerically evaluate the effects of charging CCB on the blast furnace operation. For each simulating case, the inflow conditions of blast and pulverized coal are maintained, and the hot metal temperature is kept equivalent by adjusting the mass ratio of iron-bearing burdens to coke through trial-and-error method. The numerical calculation shows that stable operations with lower in-furnace temperature level can be achieved with the CCB charging. With increase in the CCB charging ratio, the position of cohesive zone shifts downwards and the temperature of the thermal reserve zone shows an obvious decrease. For 30 % CCB charging case, the reserve zone temperature is lowered by over 200 $^{o}$C. The predicted results also reveal that the reduction of CCB is retarded with CCB charging ratio. For the range of CCB charging ratio tested, the decrease in heat requirements for solution loss, sinter reduction and silicon transfer reactions, heat taken away by top gas and wall heat transfer, makes it possible to improve the efficiency of the blast furnace with CCB charging ratio increasing. For charging 30 % CCB, the productivity is increased by about 12.0 %, coke rate and total reducing agent rate are reduced by 30.2 % and 6.3 %, respectively, compared with base case (without CCB charging). Therefore, charging carbon composite agglomerates is expected to effectively improve the performance of the blast furnace.

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