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MULTI-DIMENSIONAL MATHEMATICAL MODEL OF BLAST FURNACE BASED ON MULTI-FLUID THEORY AND ITS APPLICATION TO DEVELOP SUPER-HIGH EFFICIENCY OPERATIONS

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ABSTRACT

This paper mainly emphasizes development of a multi-fluid blast furnace model and its application to simulate several innovative ironmaking operations. At first, the development process and framework of the model are briefly introduced. Then, model simulations on hydrogen bearer injection show that the enhancement of hydrogen reduction brings the improvement of furnace performance, especially for injection of natural gas and plastics. Total heat input shows obvious decrease due to the decrease in direct reduction, solution loss and Si transfer reactions. Also, another simulation shows that if carbon composite agglomerates are charged in the furnace thermal reserve zone temperature will obviously decrease, and the reduction of iron-bearing raw materials will be retarded. However, the efficiency of blast furnace is improved due to the decrease in heat requirements for solution loss, sinter reduction and silicon transfer reactions, and less heat outflow by top gas and wall heat loss. The third application is to investigate the performance of blast furnace under top gas recycling together with plastics injection, cold oxygen blasting and carbon composite agglomerates charging. The model predicted lower in-furnace temperature, extremely accelerated reduction speed, drastically decreased carbon emission and remarkably enhanced heat efficiency. Thus, the blast furnace operation with super high efficiency can be achieved through the practical applications of these innovative technologies.

KEYWORDS: Ironmaking, Blast furnace, Mathematical model, Tuyere injection, Top gas recycling, Multi-fluid model

INTRODUCTION

To date, blast furnace operators have a relatively good understanding of internal mechanisms, and no longer treat the blast furnace as “black box”. However, the blast furnace is one of the most complex metallurgical units in the field of chemical engineering, the complexity keeps proliferation with the adoption of new technologies, such as high rate injection of pulverized coal, effective use of carbonaceous and ferrous materials, and so on. If merely by direct instrumentation and empirical knowledge, it is impossible to obtain full understanding of inner phenomena, accurate prediction on the effect of parameter changes, precise control and further improvement of the operations. As a consequence, a number of attempts have been made to construct mathematical models for blast furnace operation analysis.

According to the methods for describing the blast furnace process, the mathematical models can be classified into heat and mass balance models, reaction-kinetic models and equilibrium models. The mathematical models based on chemical kinetics and transport phenomena theory are useful tools for better understanding, control and improvement of the complicated blast furnace process. The authors have developed a multi-dimensional transient mathematical simulator of the blast furnace operation, named multi-fluid blast furnace model (Austin, et al., 1997, Castro, et al., 2000, 2002).

The blast furnace has contributed significantly and still maintains its predominant position as a mass producer of hot metal. In 2002, the blast furnace process produced 96 % of hot metal all over the world. Blast furnace system (sintering machine, coke oven, blast furnace and hot stove) is the most energy-consuming for the whole steelmaking process. Furthermore, majority of CO_2 emission from the steel industry is generated in this system. In 2002, the blast furnace system took up 69.4 % of energy consumption and 73.4 % of CO_2 emission in total steel industry, and that of blast furnace corresponds to 49.0 and 53.0 %, respectively (MITI, 2003). Noticeably, blast furnace is the core of an integrated steelworks, and any improvement in the furnace efficiency is of great importance for steel industry and even for whole society.

Thus, it is expected to further reduce consumption of energy and resource to decrease environmental load while intensifying production for the current blast furnaces. However, It is quite difficult to attain this goal under worsening trends of raw materials and the other factors if only depend on conventional technologies. On these backgrounds, a number of innovative technologies have been proposed, including: 1) hydrogen bearing materials injection; 2) charging carbon composite agglomerates; and 3) top gas recycling. As the first step before practical applications, these innovative operations are simulated by means of the multi-fluid blast furnace model, which are of great importance to investigate the response of blast furnace to innovative operations, verify how much the furnace efficiency could be improved, and analyze the possibly-occurred problems and put forth the corresponding countermeasures.

MULTI-FLUID BLAST FURNACE MODEL

Developing Process of Blast Furnace Models

Muchi et al. (1966) originally proposed a one-dimensional model which considered major chemical reactions and heat transfer and gave the distributions of process variables along furnace height. A number of models have been developed extending this modeling technique. In early days, in-furnace transport of materials and energy are described by ordinary differential equations even in transient and quasi-multi-dimensional models. In the 1980's the evolution of computer technologies allowed the models to handle large matrix, and the models started to use partial differential equations as their governing equations. This change offered the fundamentals to describe in-furnace phenomena in more detail. In the beginning of 1990's, a general idea was proposed. This is to describe the phenomena occurred in the lower zone as multi-phase flow with mutual inter-phase interactions (Yagi, 1993). This concept classified the phases by flow mechanism, thus it treated fine powders entrained by gas stream as a phase in addition to gas, solid and liquid phases as physical states of matters. This concept is so called "four-fluid model". In the development of blast furnace models based on this concept, liquid and powder phases were further divided into two phases each by the differences in physical properties. The present multi-fluid blast furnace models are able to solve two- and three-dimensional problems in steady state or transient (Austin, et al., 1997, Castro, et al., 2000, 2002).

Framework of Multi-fluid Model

The mathematical model used here 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 the 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 and plastics) 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 equation for each phase can be expressed in a single generalized form as written below:

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

Where, the variable ψ represents the variables to be solved. By changing ψ, this general equation represents the conservation of mass, momentum, enthalpy and chemical species for each phase "*i*" considered in the model. Γ_ψ is the effective diffusive transfer coefficient, which assumes a different meaning for each dependent variable to be solved. Additionally, S_ψ 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, ζ takes the same dependent variable as ψ. But for enthalpy conservation, $\psi = H_i$ while $\zeta = T_i$, and the conductive heat transfer terms become source term.

All conservation equations are solved simultaneously. The furnace is represented by a numerical grid based on body-fitted coordinate (Thompson, et al, 1985), and the governing conservation equations are discretized over the numerical grid using control volume method (Tseitlin, et al., 1994). The SIMPLE (Patankar and Spalding, 1972) scheme and iterative matrix method are used to solve the equations. The model calculation gives the distribution of process variables (velocity component, temperature, reduction rate, reduction degree, etc) and the overall operational parameters (productivity, reducing agent rate, CO and H_2 utilization and so on).

MODEL SIMULATION ON INNOVATIVE OPERATIONS

Injection of Hydrogen Bearing Materials

Injection of hydrogen bearing matters (steam, natural gas and waste plastics in this study) into blast furnace is just based on the following considerations: the first one is to enhance hydrogen involvement in reduction of iron oxide since H_2 is much more favorable than CO as reductant. The second one is that gas product of hydrogen reduction is steam, not CO_2. Consequently, it is expectable to improve indirect reduction, lower energy consumption and decrease CO_2 emission through injection of hydrogen bearing materials (Chu, et al, 2004b).

In this study, four cases with all-coke operation, 80 g-H_2O/Nm^3 humidified blasting (HB), 140 kg/thm natural gas injection (NGI) and 40 kg/thm waste plastics injection (PLI) were numerically analyzed. To compare these operations, the heat supply from raceway zone (mainly including raceway temperature and bosh gas flow rate) and the temperature of hot metal were kept constant throughout all the cases. These were 2,098C for raceway temperature, 90.0NM^3/s for bosh gas flow rate and 1,597C for hot metal temperature at slag surface. The simulation shows that: hydrogen is enriched in the furnace gas with the injection of hydrogen bearer, and the ratios of hydrogen reduction to the entire indirect reduction, especially for the reduction of magnetite and wustite, are remarkably increased, as shown in Table 1.

Case	Hydrogen reduction ratio [%]		
	$Fe_2O_3 \rightarrow Fe_3O_4$	$Fe_3O_4 \rightarrow FeO$	$FeO \rightarrow Fe$
All-coke	0.4	11.2	28.6
HB	2.5	34.9	53.5
NGI	10.9	79.8	74.4
PLI	1.2	27.0	49.3

Table 1: The ratios of hydrogen reduction to the entire indirect reduction

The major operation parameters are predicted under hydrogen bearer injection, as shown in Table 2. The productivity is evidently increased corresponding to the injection of hydrogen bearer together with oxygen enrichment. Enhancement of hydrogen involvement makes reduction of iron oxides faster and it decreases direct reduction in liquid slag. Coke rate shows significant decrease in NGI and PLI while HB operation consumes more coke than all-coke operation due to no combustion heat from steam. Total heat input, however, shows obvious decrease. This is due to the decrease in direct reduction, solution loss and Si transfer reactions. In general, the furnace performance is improved with hydrogen bearer injection.

Case	All-coke	HB	NGI	PLI
Productivity [t/day]	4499	5143	6260	4844
Direct reduct'n [-]	0.067	0.02	0	0.055
Coke rate [kg/thm]	523	537	342	453
Input heat [GJ/thm]	4.39	3.82	3.22	4.01

Table 2: Calculated operation parameters for hydrogen bearer injection

Carbon Composite Agglomerates Charging

The carbon composite agglomerates (hereinafter CCB), the mixture of fine coal and fine iron ore after hot briquetting process, have been attracting much attention as a new raw material for ironmaking from the viewpoints of energy saving, resource recycling and environmental protection. Compared with the other carbon containing agglomerates, the CCB shows better reducibility, lower cost and higher strength (Kasai et al., 2001).

The effect of CCB charging on blast furnace performance was examined by a modified multi-fluid blast furnace model (Chu, et al, 2004a). The CCB was assumed to consist of hematite (75 %), carbon (20 %) and gangue (5 %) and treated as a component of packed solid phase. For CCB, carbon reduction, solution loss, melting, carburization and combustion were newly considered in the model.

This study investigates four different cases, in which mass percentage of CCB in iron bearing burdens (sinter and CCB) is 0, 10, 20 and 30 %. The first one is a conventional operation without CCB charging, which is selected as base case. Model simulations reveal that furnace temperature decreases when CCB is charged as shown in Figure 1. The temperature of thermal reserve zone decreases by about 200 °C in 30 % CCB charging case compared with the base case without CCB charging. With the temperature decrease, reduction of both sinter and CCB is retarded.

Figure 2 summarizes the effect of CCB charging on productivity, slag rate and reducing agent consumption. The productivity shows evident increase with CCB charging ratio while slag rate tends to decrease. If the percentage of CCB in iron-bearing burdens increases from 0 to 30 %, hot metal productivity is improved by 6.7 %, and the predicted slag rate is lowered by 7.7 %. Regarding to reducing agent rate, the carbon in CCB is proportionally increased with the CCB ratio, pulverized coal rate slightly decreased due to the increase in hot metal productivity, coke rate showed remarkable decrease. Total RAR also decreased by 4.4 % in 30 % CCB case. The simulation shows that charging CCB within tested range can improve the efficiency of blast furnace despite that in-furnace temperature level tends to decrease and reduction is retarded, which is due to the decrease in heat requirements for solution loss, sinter reduction and Silicon transfer reactions, and less heat outflow by top gas and wall heat loss.

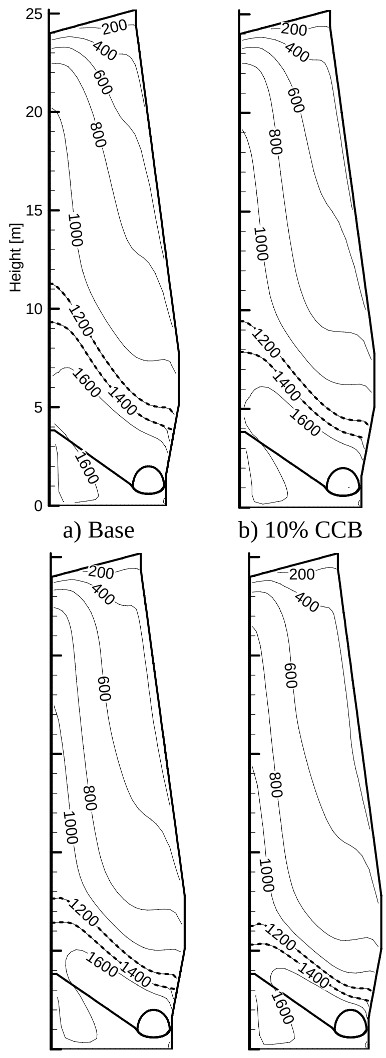


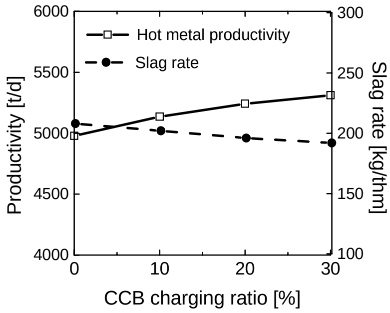
Figure 1: Effect of CCB charging on solid temperature distribution [unit: °C].

Top Gas Recycling

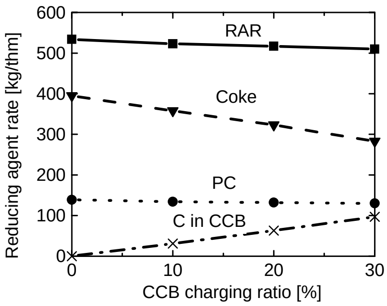
Top gas recycling has been considered as an effective method to improve the blast furnace performance by enhancing the utilization of carbon and hydrogen and by reducing the emission of carbon oxides. The method of top gas recycling (Murai, et al., 2002) studied here is shown in Figure 3. Note that, CO_2 in top gas is removed before injection. The multi-fluid model is used to predict the performance of blast furnace operations with top gas recycling, together with CCB charging and waste plastics injection.

Evaluating Conditions

The blast furnace analyzed here has hearth diameter of 14.0 m, height of 32.4 m and inner volume of 4288 m^3. Four operation cases are numerically evaluated. The first case stands for conventional operation with no CCB charging and no top gas recycling, which is indexed as base case. The operation conditions in the base case include blast rate 5698 Nm^3/min, blast temperature 1200 ^oC, oxygen enrichment 8 %, coke rate 269 kg/thm, pulverized coal rate 249 kg/thm and productivity 8332 t/d. The second case is specified as CCB20-PLA, in which



a) Productivity



b) Reducing agent rate

Figure. 2: Predicted operational parameters for CCB charging.

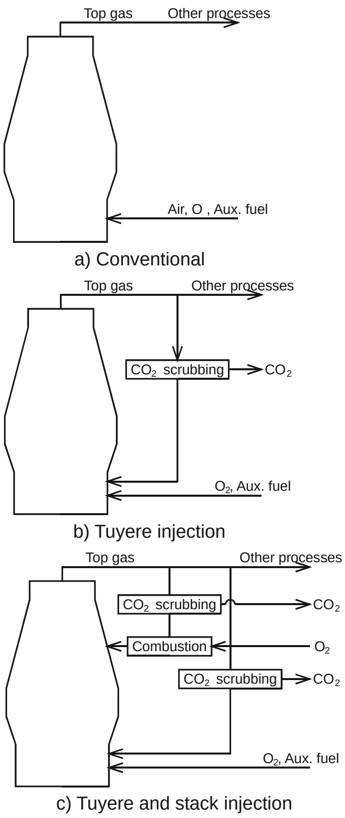


Figure 3: Methods of top gas recycling.

20 % of sinter is replaced by CCB and the conditions of blast and injection include blast temperature 1070 ^oC, blast rate 5708 Nm^3/min, oxygen enrichment 5 %, waste plastics injection rate 119 kg/thm. The third case with tuyere injection of top gas is indexed as TI, where CCB charging ratio is also 20 %, top gas 2562 Nm^3/min and pure oxygen 2184 Nm^3/min are simultaneously injected into tuyere at 25 ^oC and injection rate of plastics is 128 kg/thm. The last case with both shaft injection and tuyere injection is indexed as SI-TI. The conditions of tuyere injection include simultaneous injection of treated top gas 2564 Nm^3/min and pure oxygen 2184 Nm^3/min at 25 ^oC besides waste plastics 118 kg/thm. For shaft injection, the treated top gas after reheated to 900 ^oC is injected to shaft location (height 12 m) with the rate of 2702 Nm^3/min. Throughout the simulations, bosh gas flow rate, raceway temperature and hot metal temperature are kept constant at 8130 Nm^3/min, 2197 and 1570 ^oC.

Simulation Results

Figure 4 shows the distributions of solid temperature in base, CCB20-PLA, TI and SI-TI cases. Compared with the base case, the shaft temperature shows remarkable decrease and cohesive zone shifts downward in CCB20-PLA case, which is attributed to strongly endothermic effects of CCB reduction. In TI case, in-furnace temperature tends to decrease in the wider region from upper to mid zones, cohesive zone is lowered near to deadman zone and steep temperature gradient appears in the lower zone.

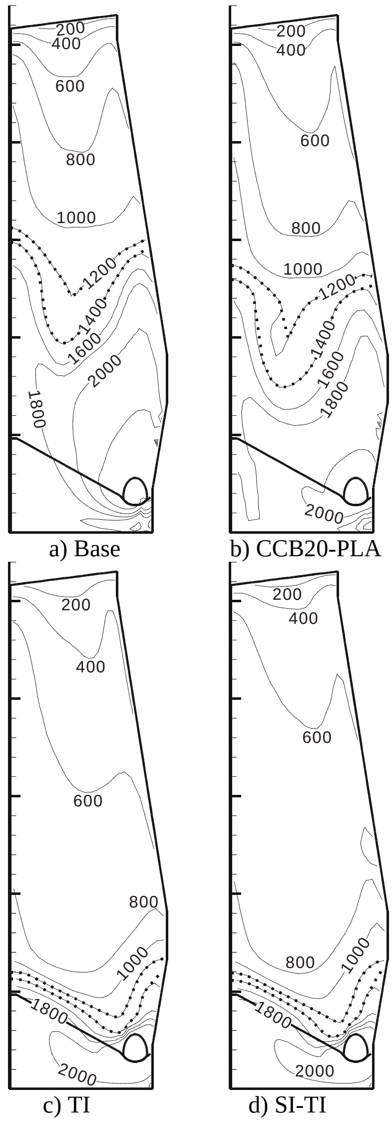


Figure 4: Distributions of in-furnace solid temperature [^oC].

Figure 5 shows the distributions of H_2 concentration. H_2 concentration increases a little in CCB20-PLA case. However, more remarkable increase in H_2 concentrations is estimated in whole furnace for TI and SI-TI cases, especially in shaft region of the latter, owing to injection of plastics and top gas.

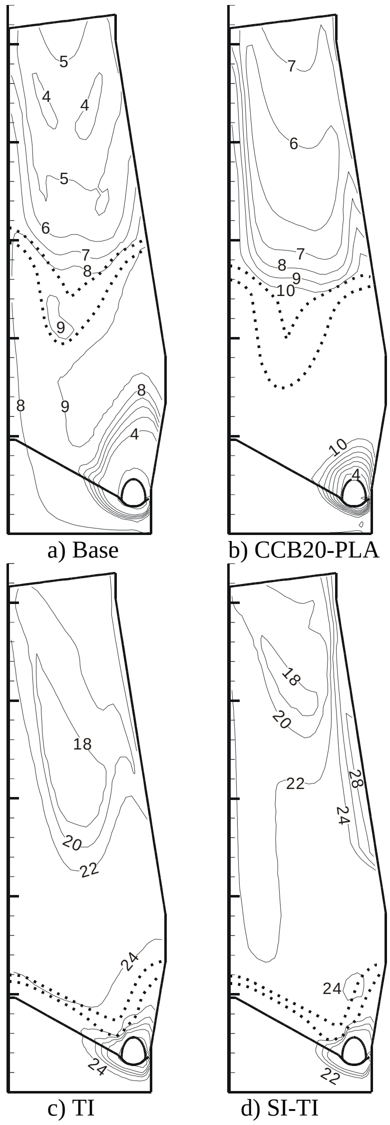


Figure 5: Distributions of H_2 concentration [mol-%].

Figure 6 shows the reduction of sinter. In CCB20-PLA case, the reduction of sinter proceeds faster than that in the base case and nearly completes before melting, which is due to the higher H_2 concentration and lower solid charging rate. In TI case, reduction of sinter is much faster due to simultaneous increase in H_2 and CO concentrations despite lower temperature level, and even overall reduction completed before reaching 800 ^{o}C isothermal zone. Additionally, in SI-TI case the improvement of sinter reduction in shaft is much more remarkable, directly resulted from shaft injection heat and higher reducing gas concentrations.

The information of primary operation parameters is summarized in Table 3. The first is about changing tendency of productivity. Compared with the base case, the predicted productivity tends to decrease by 10.9 % in CCB20-PLA case. However, it shows an increase by 5.5 % in TI case, and bigger increase by 14.0 % in SI-TI case. Different tendencies are due to the effects of oxygen

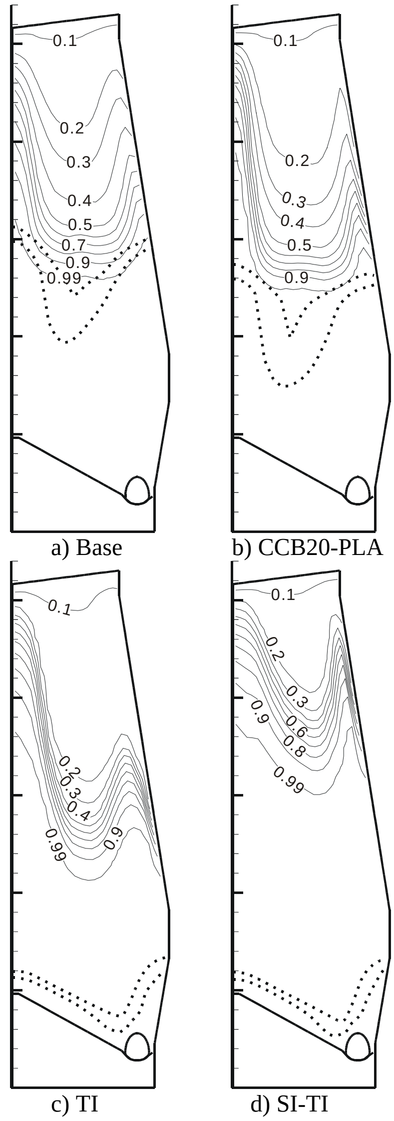


Figure 6: Distributions of overall reduction degree [-].

Item	Base	CCB20-PLA	TI	SI-TI
Productivity [t/d]	8332	7421	8789	9500
RAR [kg/thm]	518	487	540	505
Coke rate [kg/thm]	269	304	347	321
PC/PLA rate [kg/thm]	249	119	128	118
Carbon in CCB [kg/thm]	0	64	65	65
C emission rate [kg-C/thm]	392	380	313	225
Total heat input [GJ/thm]	6.10	5.95	5.23	5.33

Table 3: Predicted operation parameters.

inflow rate and/or mass ratio of iron bearing burdens to coke.

DISCUSSIONS

Numerical evaluations reveal the blast furnace operations with super high efficiency can be achieved through the applications of the innovative technologies. With injection of hydrogen bearing matters, CCB charging and top gas recycling: 1) The production is remarkably intensified; 2) Energy consumption is tremendously reduced; 3) Environment load is significantly lowered. The following perspectives can be made for the future blast furnace with super high efficiency, including: 1) the blast furnace can be compact. The shaft height is possible to shorten (evidently proved by SI-TI case in Fig. 6); 2) The furnace can accept inferior raw materials and fuels more flexible than conventional furnace by using carbon composite agglomerates. In addition, low strength coke can be used due to lower in-furnace temperature and the shorter height of the furnace; 3) The optimization and simplification of the overall blast furnace system are available. The annexed facilities like hot stove and coke oven can be made smaller. In some case with top gas recycling, the hot stove is not needed; 4) The variety of injectants will be diversified, which consist of treated top gas, waste plastics, pulverized coal and the other reducing gas.

CONCLUSIONS

This paper mainly emphasized multi-fluid blast furnace model and its application to simulate several innovative ironmaking operations. At first, the development process and framework of the model were simply introduced. Then, model simulations on hydrogen bearer injection showed that: the enhancement of hydrogen reduction improved furnace performance, especially for injection of natural gas and plastics. Another simulation showed that carbon composite agglomerate charging into the furnace decreased thermal reserve zone temperature and retarded the reduction of iron-bearing materials. However, the efficiency of the blast furnace was improved due to the decrease in heat requirements. The final application was to investigate the blast furnace operations under top gas recycling together with plastics injection, cold oxygen blasting and carbon composite agglomerates charging. The model predicted decrease in-furnace temperature, extremely accelerated reduction speed, drastically decreased CO_2 emission and remarkably enhanced heat efficiency. Thus, the blast furnace operation with super high efficiency could be achieved through the practical applications of these innovative technologies.

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