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Development of Mathematical Model of Blast Furnace

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Abstract

As for the mathematics model of a blast furnace of Nippon Steel Corp., development has been mainly done centering on the model that estimated material transfer, reaction and heat transfer of lumpy zone or cohesive zone. In parallel with this, a burden distribution model, a reaction model of tuyre and raceway, a model concerning of deadman and of a furnace hearth are developed and approximately cover the whole blast furnace. These models have been used for the analysis and the operation design of actual operation. In addition, we are developing a model with a disintegration element method and a non-steady model recently.

1. Introduction

Nippon Steel Corporation has developed many different blast furnace models—the one-dimensional blast furnace models developed by Miyasaka et al. and Kenno et al., respectively[1-3], two-dimensional total blast furnace model, model for predicting the burden distribution at blast furnace top, tuyere/raceway models and hearth models, to mention only a few. In this paper, those models are reviewed and new blast furnace models to be developed in the future are discussed.

2. Overview of Mathematical Blast Furnace Models

At Nippon Steel Corporation, mathematical blast furnace models have been developed chiefly to estimate the mass transfer, reactions and heat transfer in lumpy and cohesive zones. On the other hand, models for estimating the burden distribution at the furnace top, tuyere and raceway reaction models and models for estimating the heat transfer and fluidity in the deadman and hearth have also been developed. All these models cover almost the entire aspect of blast furnace operation. Recently, models using the distinct element method and those taking non-steady states into account are also being developed.

2.1 Two-dimensional total blast furnace model

The two-dimensional total blast furnace model has been developed to obtain two-dimensional information about the cohesive zone profile and gas/temperature distributions in the blast furnace. Aside from this total model, various other models for estimating cohesive zones have been developed[4-9].

The two-dimensional total blast furnace model, which is based on the BRIGHT (Blast furnace Realization for Instruction Guide by Hybrid Theory) model developed by Sugiyama et al.[10, 11], integrates various models, including the burden distribution model[12, 13]. In order to improve the accuracy of the conventional reduction model (greater accuracy was demanded by the diversification in raw materials and fuels used and blast furnace operation conditions), the total model has incorporated a multistage reducing reaction model[14, 15], and a modified high-temperature property model[16], etc. As the new BRIGHT model (N-BRIGHT model), it is used to analyze various phenomena that occur within the blast furnace. This is not to say that the N-BRIGHT model is always used off-line[17,18]. When built into a process computer, the model permits the display of calculation results on-line in the operation room. Thus, it can be effectively used to determine blast furnace operation policy as well (**Fig. 1**).

1) BRIGHT model

When it comes to changing certain operational conditions for an actual blast furnace, it is necessary to predict how the cohesive zone profile and phenomena in the furnace respond to such change. However, in the case of a blast furnace, which is a large and complicated system, using an actual blast furnace to determine the effect of a specific factor experimentally takes much time and money. Besides, since the in-furnace phenomena reflect complicated interactions of gas/solid flows, as well as mass and heat transfers, in order to acquire thorough knowledge of the in-furnace phenomena from data obtained by sensors and basic experiments, etc. and apply such knowledge to actual blast furnace operations, it is necessary to employ a theoretical mathematical model that combines the above factors or-

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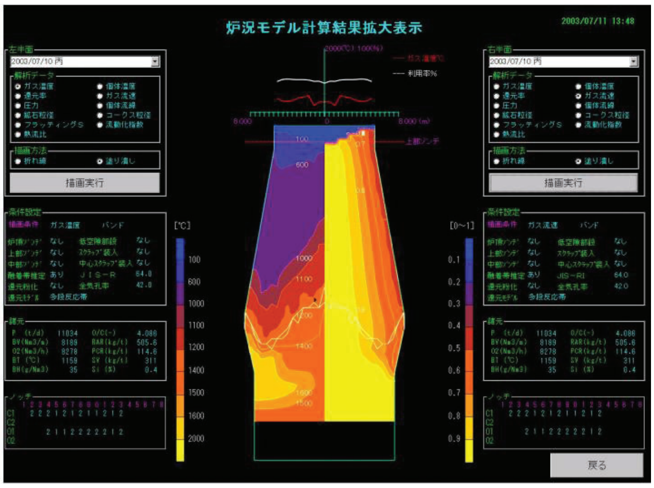


Fig. 1 Display of calculation result of N-BRIGHT Model at operating room

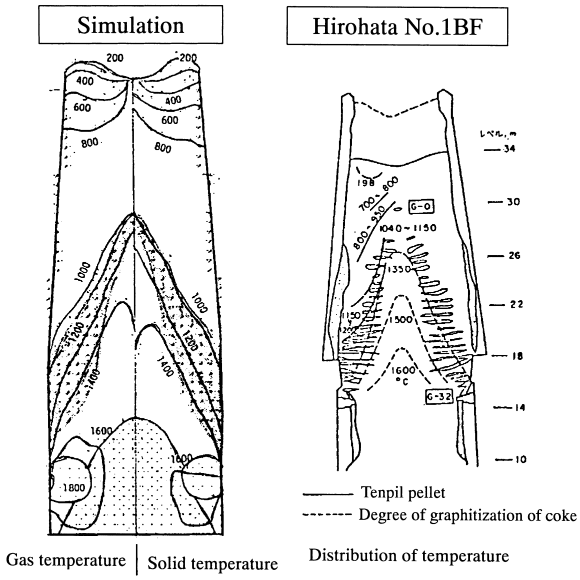


Fig. 3 Comparison between model calculation result and dismantling blast furnace finding

ganically. Therefore, a two-dimensional mathematical model was developed that permits deduction of the estimated gas/solid flows, temperatures and reactions in the blast furnace from particular operational conditions. As shown in **Fig. 2**, this model is made up of several sub-models—namely the burden distribution, gas flow, solid flow, chemical reaction, liquid flow and heat transfer sub-models. The total blast furnace model which integrates all these sub-models is used to calculate the cohesive zone profile (**Fig. 3**).

The model has these characteristics: (1) it is applicable to all blast furnaces, (2) it is a theoretical model allowing for simultaneous analysis of solid/gaseous flows, reactions and heat transfer, (3) it places the major emphasis on two-dimensional burden distribution in furnace radial direction, (4) it permits theoretical estimation of cohesive zone profiles, (5) it does not always require input of data obtained by probes, though input of probe data is possible, (6) it allows for theoretical experiments and drastic changes of operational conditions that cannot be tested in an actual blast furnace, and (7) it readily permits reflection of the results of basic experiments.

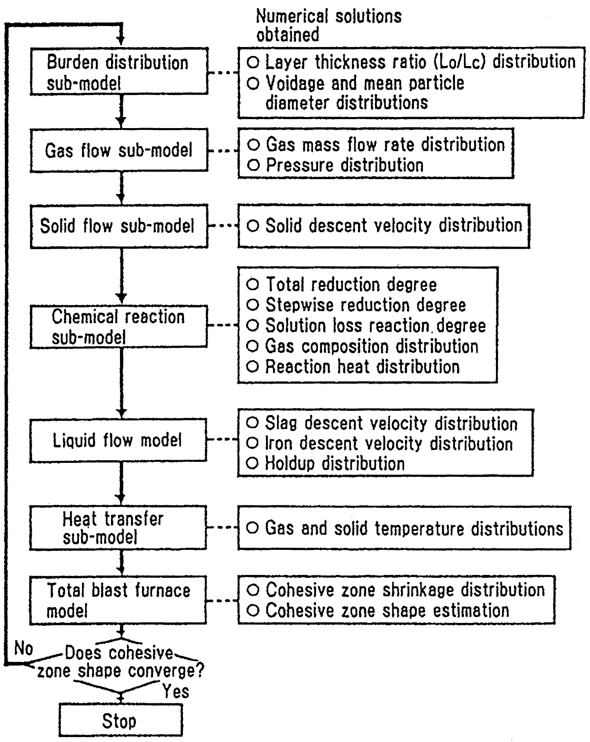


Fig. 2 Basic concept of model

2) N-BRIGHT model incorporating multistage reaction zone model

The N-BRIGHT model incorporates a multistage reaction zone model—a highly sophisticated version of the reduction model that is the most important constituent of the total blast furnace model. As a sinter reduction model, the one-interface model that allows for easy analysis or the multi-interface unreacted core shrinking model has been used. The BRIGHT model incorporated a three-interface unreacted core shrinking model. However, since it could not fully reflect the difference in sinter properties on the in-furnace phenomena, the multistage reaction zone model developed by Naito et al. has been incorporated in the N-BRIGHT model. The multistage reaction zone model assumes that hematite, magnetite, wustite and iron ore continue reacting hand in hand, rather than independently of one another with a definite boundary between them as assumed by the three-interface unreacted core shrinking model. With this model, it has become possible to obtain calculation results that agree well with measurement results obtained in an actual blast furnace and experimental results on reductions obtained in a BIS furnace, etc.[19-21] (**Fig. 4**).

3) Model for estimating Silicon in hot metal

To predict the silicon content of hot metal, studies have been made based on the theory of equilibrium that assumes that in a blast furnace, the slag and metal[22] or FeO and Si[23] are kept in equilibrium. Actually, however, the results of sampling tests in a blast furnace during operation did not reveal thermodynamic equilibrium in the raceway. Therefore, a model was built to predict the Si distribution in the blast furnace based on the theory of moving velocity[24]. The initial conditions for this model, such as the gas flow velocity, are given from calculation results obtained by the total blast furnace model. The results of calculations with this estimation model have clarified a number of facts—that the generation of SiO gas from the

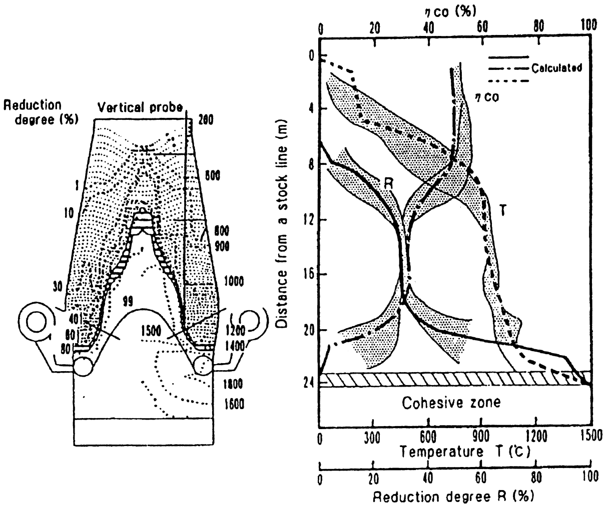


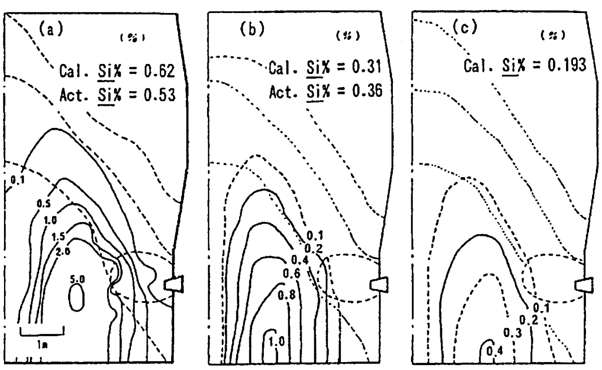
Fig. 4 Comparison between analyzed values and values measured with probes in Oita Works No.2 blast furnace

coke and slag in the neighborhood of the raceway can be explained not by the equilibrium theory, but by the transfer kinetics, and that the rate of SiO generation from coke is the most important factor influencing the Si concentration in hot metal (**Fig. 5**).

4) Reduction degradation model

As one of the phenomena that influence permeability in a blast furnace, the generation of powder due to degradation of raw materials/fuels in the shaft and lower part of the furnace can be cited. With the BRIGHT model, in principle, the burden boundary conditions given are only those at the furnace top. However, it is already known that the particle size distribution and void fraction distribution in the blast furnace vary in vertical and radial directions because, for example, the charged sinter is subject to reduction degradation in the furnace. Since this phenomenon significantly affects permeability in the furnace, the matrix method was introduced to create a reduction degradation model based on the reduction degradation estimation equation developed by Iwanaga et al.[25]. This model has made it possible to simulate the formation of a low temperature heat retention zone due to an increase in reduction degradation with the increase in the reduction degradation index (RDI) of the sinter[26] (**Fig. 6**).

5) Powder movement/accumulation model



a) Tf=2325℃, ε=0.36 b) Tf=2157℃, ε=0.36 c) Tf=2157℃, ε=0.42

Fig. 5 Influence of void fraction of deadman and flame temperature at tuyer on Si distribution of lower part of blast furnace

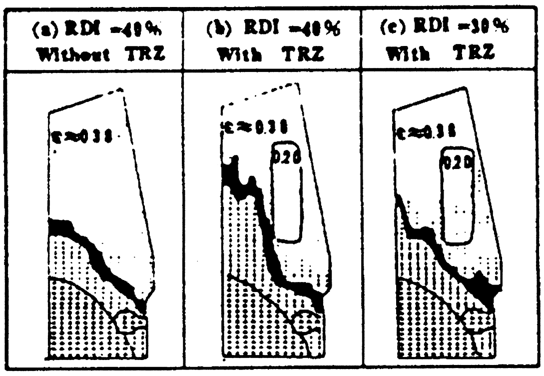


Fig. 6 Relation between cohesive zone and RDI (TRZ: thermal reserve zone)

The phenomenon of degradation of raw materials/fuels in the blast furnace is not limited to the reduction degradation of sinter. In the lower part of the furnace, considerable amounts of powder occur due to degradation of raw materials/fuels. In blast furnace operations that use a large proportion of pulverized coal, in particular, the degradation of coal due to a low coke ratio and the behavior of unburned pulverized coal are problematic. Therefore, on the basis of the results of model experiments, a model was created to estimate the movement and accumulation of powder that occurs in the lower part of the furnace. The movement of powder was formulated by using the mass of the powder and the gas acceleration, etc. derived from the Fanning equation of gravitation, and the equation of powder hold-up was obtained by summing up the experimental results using non-dimensional numbers. With this model incorporated into the total blast furnace model, it has become possible to clarify the influence of the powder accumulation behavior in the furnace on the permeability[27, 28] (**Fig. 7**).

6) Model of liquid flow in blast furnace dripping zone[29]

The liquid flow in the dripping zone of a blast furnace significantly influences the gas permeability, heat transfer in the deadman and reducing reaction of FeO. With the aim of creating a model of the liquid flow in the dripping zone, model experiments were conducted to formulate liquid hold-up, liquid dripping rate, and liquid flow velocity distribution, etc. The basic structure of the model created is of two-dimensional axial symmetry. The model uses a viscous resistance equation of Darcy formula type to calculate liquid

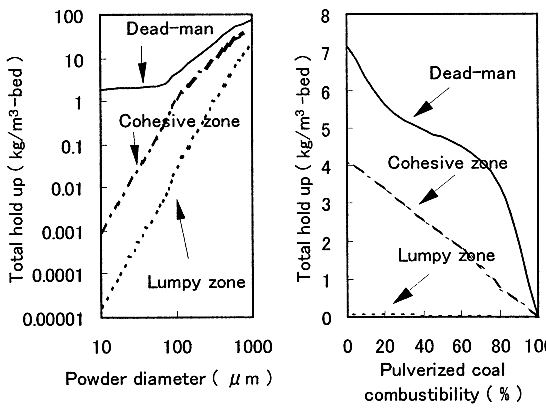


Fig. 7 Effect of powder diameter and pulverized coal combustibility on the total hold up

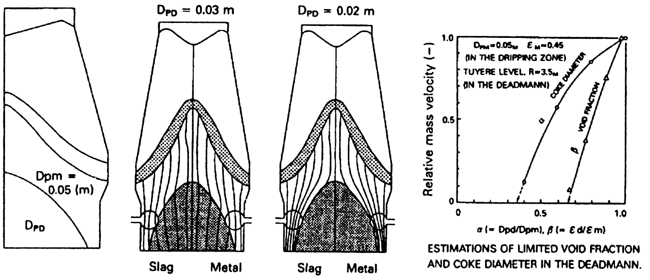


Fig. 8 Effect of coke diameter on slag and pig iron flow in the lower part of blast furnace

permeability resistance. The combination of this model and the slag viscosity estimation model described later has made it possible to study the influences of heat transfer and void fraction on liquid permeability in the deadman (**Fig. 8**).

2.2 Blast furnace burden distribution model[30-32]

Models for predicting the burden distribution in a blast furnace were actively developed in the 1980s. The RABIT (RAdial Burden distribution Index Theoretical) model, which gives important initial conditions to the total blast furnace model, has been used in design and analysis of blast furnace operations.

The RABIT model is characteristic in that it takes into account the influences on the burden distribution mode of the gas flow, coke collapse phenomena, burden descent, etc. in the furnace that significantly affect the mode of burden distribution in the central part of the furnace. Those influences were formulated based on the results of studies using model experimental apparatus, etc. As shown in **Fig. 9**, this model consists mainly of the burden fall/deposition process, particle size distribution process, coke collapse phenomena and gas flow distribution process. Of these, the calculation steps for deposit profile/particle size distribution and coke collapse phenomena are especially important (Figs. 9 and **10**).

Following development of the RABIT model, new types of charging equipment and new methods of blast furnace control have been developed. Therefore, several new sub-models were and incorporated into the RABIT model as described below.

1) Void fraction estimation sub-model

The void fraction of the particle deposition layer is very important in estimating the gas flow in the blast furnace. A void fraction

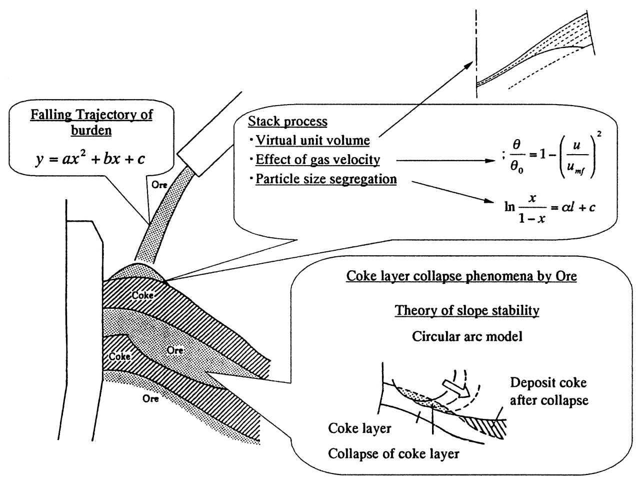


Fig. 9 Basic idea of model

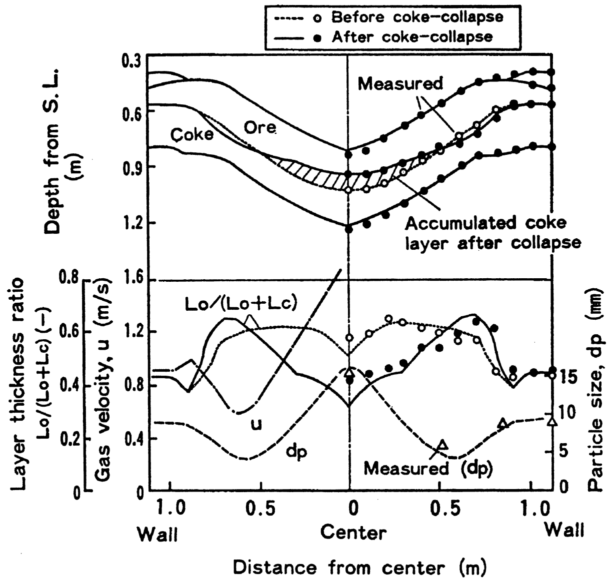


Fig. 10 Comparison of calculation result and measurement results by model experiment

estimation equation that takes into account the particle size distribution has been proposed by Ichida et al.[33]. This equation represents a sub-model that applies to the sinter and coke an estimation equation of multi-component particle random packing layer based on the coordination number estimation model created by Suzuki et al.[34]. This sub-model has made it possible to accurately estimate the void fraction after the particle size composition has changed.

2) Furnace wall deposit profile estimation sub-model

With the diversification of charging methods, it became necessary to improve the accuracy of burden deposit profile estimates near the furnace wall. Therefore, an off-line distribution test apparatus was developed using ultrasonic sensors to permit measuring of the deposit profile with a high degree of accuracy. On the basis of the experimental results, there were studies relating to methods for processing data about the deposit profile and inclination angle, and clarified and quantified the process of deposition. Then, on the basis of those experimental results, it was assumed that the deposit layer as a continuum of particle and handled it with a continuous function to come up with a highly accurate, general-purpose estimation model[35, 36] (**Fig. 11**).

3) Discharged particle size estimation sub-model

The raw materials and fuels used in a blast furnace are subject to segregation during transportation, as well as when they are charged into the furnace. Therefore, in order to accurately predict the radial burden particle distribution in the furnace, it is necessary to quantify the time-series change of particle size distribution of the burden discharged from the charging equipment. Therefore, a study was conducted relating to the time dependence of particle size distribution of the burden discharged from the rotating chute using model experimental apparatus. Assuming the size distribution of burden discharged in unit time as a logarithmic normal distribution and assuming that the variance in particle size was invariable, we created this sub-model[37, 38] (**Fig. 12**).

4) New repulsion plate-type chute

The charging equipment ordinarily used with blast furnaces is the bell type or bell-less type. Nippon Steel developed a new type of charging equipment offering better controllability. It is conventional

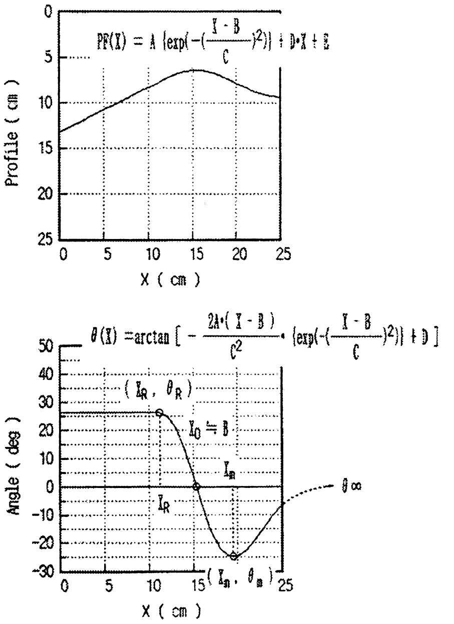


Fig. 11 Concept of definition of stack profile and inclination angle distribution function

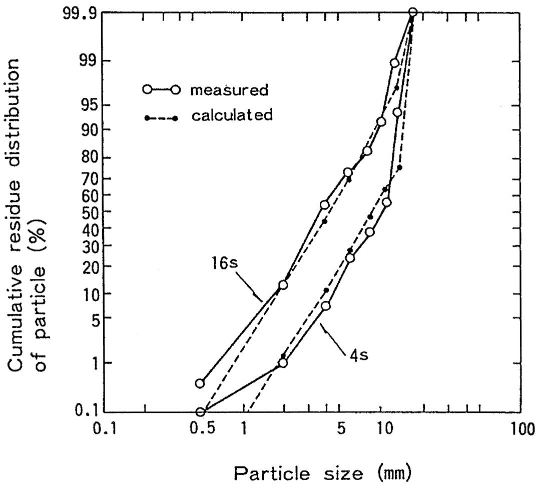


Fig. 12 Comparison between calculation and experimental results of time series change of cumulative residue distribution of particle

bell-less type charger provided with a repulsion plate at the tip of the chute. The new type of charging equipment has been introduced to Kimitsu Works No. 2, 3 and 4 blast furnaces and Hokkai Steel's No. 2 blast furnace. Suitable sub-models[39-42] have also been developed for the new-type charging equipment.

5) Two-dimensional discrete model

Technology for enhancing the blast furnace functions through charging of a mixture of coke and ore, rather than separate layers of coke and ore, has been developed. There are two examples. One involves mixing highly reactive nuts coke into the sinter ore to improve the shaft efficiency. The other involves mixing reduced iron into the ore. This is expected not only to lower the reducing agent ratio in terms of thermal mass balance but also to improve the reduction melting property of the ore layer, thereby further lowering the reducing agent ratio and increasing the productivity coefficient.

In order to bring those favorable effects of mixed charging into full play, it is important to develop a new charging method that permits charging only the required amounts of burdens which have the same particle size but differ in density and shape into appropriate parts of the furnace. In view of this, we studied the segregation characteristics of burdens during mixed charging with a model experiment, and developed a simulation model using the distinct element method to analyze the behavior of mixed layers which differ in both particle size distribution and density[43] (**Fig. 13**).

In addition, a model was studied which applied the distinct element method to bell-less charging equipment[44] (**Fig. 14**).

2.3 Tuyere raceway model

The tuyere raceway is an important part of the blast furnace for controlling the blast furnace operation. A one-dimensional model for estimating the combustion reaction of pulverized coal in the tuyere raceway has been developed by Tamura et al.[45]. This model divides

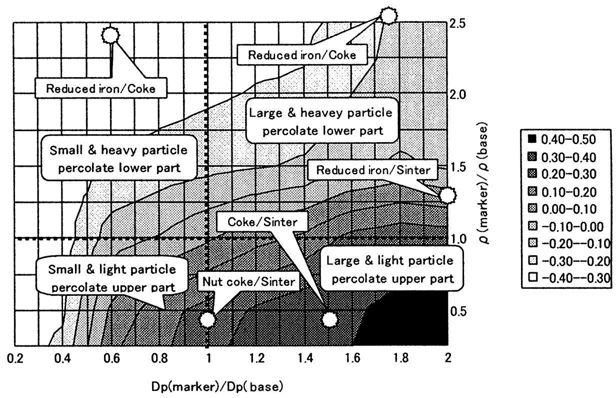


Fig. 13 Effect of particle diameter ratio and density ratio on segregation index

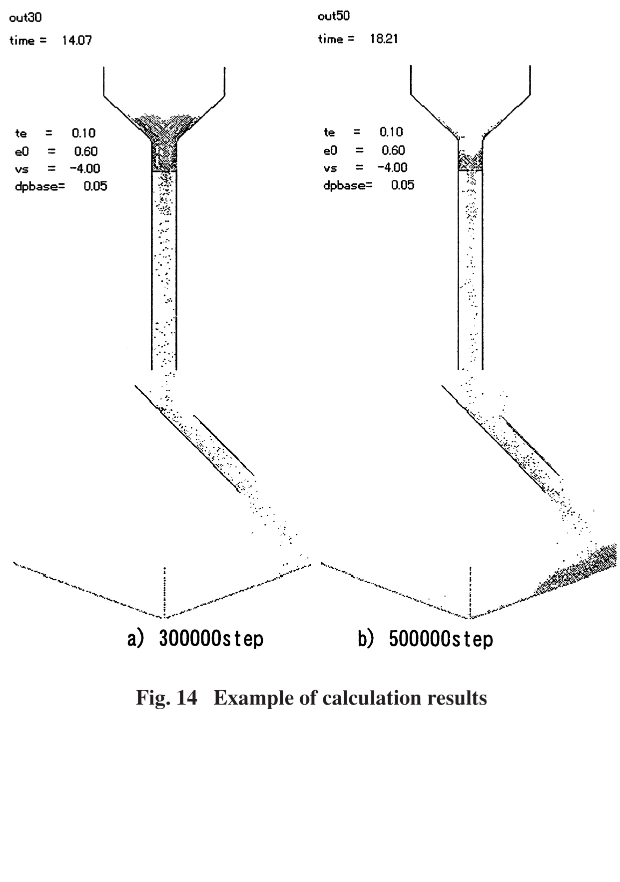


Fig. 14 Example of calculation results

the pulverized coal combustion process into a thermal decomposition process and a char combustion process to permit analyzing them separately (**Fig. 15**). This model is one-dimensional with the tuyere axis.

1) Model taking mixed coal injection into account

In recent years, with the aim of widening the choice of coals or improving the substitution ratio, technology that permits use of a mixture of coals having different proportions of volatile matter has been developed. With the above model, which gives the coal composition by average values of the individual constituents, it is impossible to simulate the combustion behavior of an actual mixture of coals. Therefore, the fundamental equation of the above model on micro-time was rewritten into one on micro-distance to determine the combustion reaction of each type of coal. Concerning the atmosphere gas, it was assumed that the gases generated by the individual coals would mix together instantaneously. As a result, it has become possible to simulate the behavior of a mixture of different coals[46] (**Fig. 16**).

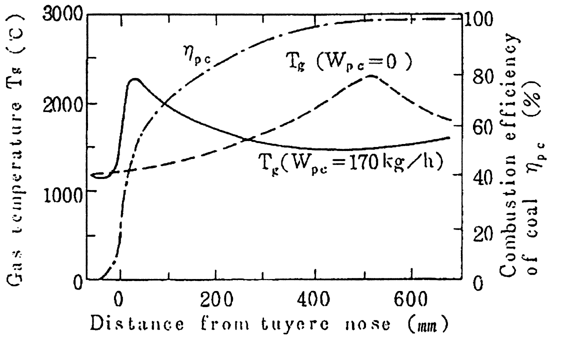


Fig. 15 Calculation result of axial distribution of gas temperature and combustion efficiency in the raceway combustion furnace

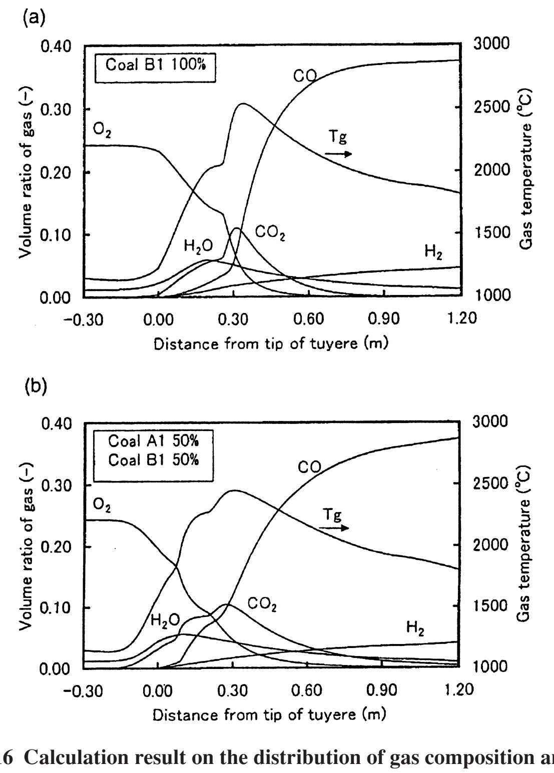


Fig. 16 Calculation result on the distribution of gas composition and temperature

2) Two-dimensional raceway model

As two-dimensional models of gas and powder flows in the raceway, a model developed by Sugiyama et al. using the Navier-Stokes equation as its fundamental equation[47] and a model developed by Shinotake et al. taking the turbulent flow into consideration[48] have been proposed. In addition, a two-dimensional model that takes into account the flow of gas and the combustion of coke has been proposed[49] (**Fig. 17**).

Although this is not a mathematical model, a raceway shape estimation equation derived from the results of a model experiment has also been proposed[50, 51]. It has been incorporated into the total blast furnace model as well.

3) Model of thermal balance in lower part of blast furnace[46]

When pulverized coal having a low volatile matter concentration and high calorific value is used, a phenomenon in which the rate of replacement with the coal improves more than the high calorific value suggests can be observed. This phenomenon can be controlled by the coal calorific value in the lower part of the furnace that takes into account the behavior of hydrogen which does not actually contribute to the exothermic reaction in the lower part of the furnace. The calorific value in the lower part of the furnace is defined as follows. It is the effective calorific value of coal in the 1,400℃ or hotter region—the dripping zone that determines the heat level of the hot metal. Namely, it is the sum of the partial combustion heat for conversion of coal into CO and the sensible heat taken in minus the heat quantity required to heat up the CO, H_2 and ash coming from the coal. Generally speaking, pulverized coal having a high calorific value in the lower part of the furnace offers a high replacement ratio and is effective in lowering the reducing agent ratio.

This model, together with the one-dimensional raceway combustion model, contributes to the widening of choice of pulverized coals.

2.4 Model of lower part of blast furnace

Because of the mounting calls for reduction of the reducing agent ratio to restrain the emission of carbon dioxide, the growing demand for higher-productivity blast furnace operations to cope with the changing economic situation and the deteriorating high-temperature

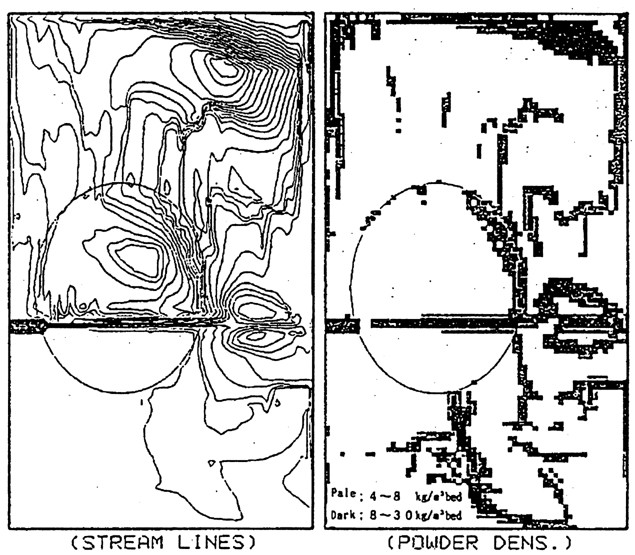


Fig. 17 Numerical solutions of gas flow at raceway

property of raw materials, the load applied to the lower part of the blast furnace has been ever increasing. In order to stabilize blast furnace operation, clarifying and controlling the behavior of the lower part of the furnace has become more important than ever before. Therefore, a model was developed for estimating the non-steady heat transfer behavior of the deadman as well as a model for estimating the flow of hot metal in the hearth. These models, together with the model of the upper part of the blast furnace, need to be developed into a total simulation model in the future.

1) Deadman non-steady heat transfer model

This is a two-dimensional non-steady model that takes into account the deadman packing structure, liquid flow, gas flow and heat transfer. Of the various reactions that take place in the deadman, only the direct reducing reaction of FeO is taken into account. Concerning the slag viscosity, the original model considered only the viscosity during the melting of slag[52]. Eventually, the model was developed into one that takes into account the slag viscosity up until the solidification of slag by incorporating a slag viscosity estimation sub-model described later[53]. This model has made it possible to measure the changes in temperature, gas permeability, liquid permeability, etc. that occur when the FeO concentration of a specific region in the lower part of the furnace sharply increases due to the occurrence of unreduced ore or inactive deadman. It should be noted that some of the boundary conditions, such as the hot metal dripping rate, are given by the N-BRIGHT model (**Fig. 18**).

2) Model of hot metal flow in hearth

This model for calculating the flow of hot metal in the hearth[54] is a steady-state model of a three-dimensional cylindrical coordinate system whose calculation region is set in the hearth at the furnace bottom. It takes into account the liquid flow and heat transfer. As for liquids, only the hot metal is taken into account: the slag is excluded from consideration. The results of calculations performed under different conditions of the hearth free zone were compared with the results of a model experiment. As a result, it was confirmed that they agreed well. Using this model and the physical properties of scale and hot metal in an actual furnace, the influences were analyzed for the rise and fall of the deadman and the presence of a solidified layer at the furnace bottom as well as for a low liquid permeability region in the deadman on the hot metal flow and temperature distribution in the hearth (**Fig. 19**).

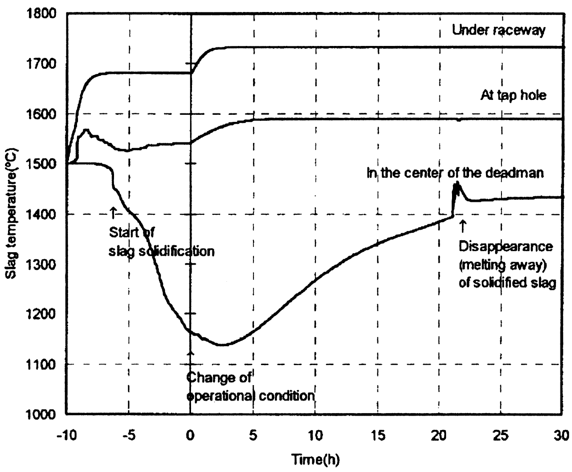


Fig. 18 Transition of the slag temperature under the effect of slag solidification and the counteraction for it

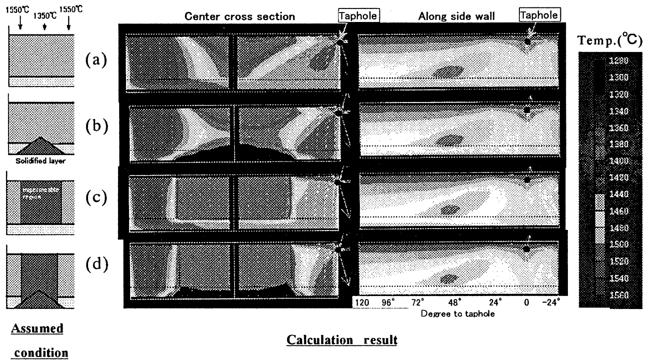


Fig. 19 Effect of solidified layer and impermeable region on liquid flow and temperature

In addition, the heat transfer was analyzed from the viscous layer to the brick of the hearth side wall using a heat transfer model[55], and estimations were made for the mechanism of damage to the hearth side wall using a thermal stress model[56] as well as analyses for the non-steady heat transfer from the hearth at the furnace bottom to the bottom brick using a suitable model[57].

3) Furnace heat model

For the lower part of the blast furnace, a number of control indexes were developed which are used in the control of heat in actual blast furnace operation, though they are not mathematical models. For example, index NSi (NMn)[58] is defined as the ratio of equilibrium value to the analyzed value of the Si concentration in hot metal (Mn concentration in hot metal). These two indexes represent the thermal leeway of the lower part of the blast furnace. As the index for judging the hearth level, estimated slag temperature[59, 60] is used. This index was obtained from analytical slag and metal temperatures when Mn, C and O were assumed to be in equilibrium. It is considered to represent the slag bath temperature in the hearth.

2.5 Blast furnace slag viscosity model

The viscosity of blast furnace slag is a very important element in blast furnace operation. The softening/shrinkage and permeability of the cohesive zone and permeability in the raceway and deadman depend considerably on the slag viscosity. On the other hand, the slag viscosity itself is influenced by the change in composition and the temperature at the time of slag formation. It is already known that the slag viscosity depends on its composition and temperature and that the presence of coke powder or the crystallization of solid phase causes it to decrease markedly. Nevertheless, there are few models that take those influences into consideration. Therefore, an attempt was made to develop a slag viscosity estimation model that takes into account the increase in slag viscosity due to precipitation of the solid phase.

To estimate the viscosity of blast furnace slag, Nippon Steel has applied the experimental recurrence equation developed by Sugiyama, Nakagawa et al.[61]. As long as the slag temperature is somewhat higher than its melting point, the calculation result obtained by the equation agrees well with the experimental result. However, when the slag temperature drops below its melting point and the solid phase begins to precipitate, the difference between the calculated and measured results widens significantly. If the solid phase ratio can be obtained, it should become possible to accurately calculate the slag viscosity even when the slag temperature drops below its melting point. Therefore, it was calculated that the solid phase ratio of slag using SOLGASMIX—a model for theoretical calculation of a phase dia-

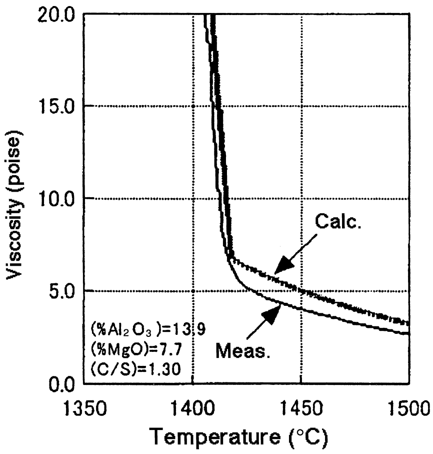


Fig. 20 Comparison of slag viscosity between measured and calculated one

gram[62, 63]—and estimated that the viscosity of suspended slag at the formation of solid phase using the relational expression developed by Mori et al.[64]. On the basis of the results obtained, a model was developed for calculating the viscosity of slag at the time of precipitation of the solid phase[65, 66] (**Fig. 20**).

2.6 Blast furnace visualization system[67-70]

This system, which is in a directly opposite position to mathematical models, gives a visual representation of the condition of a blast furnace using data collected from numerous sensors installed in the blast furnace. In the future, we intend to clarify the degree of deviation of theoretical values from actual values by comparing the results obtained with this system with the results of calculations using a physical model on a real-time basis and apply the system to early detect any transitory conditions in the blast furnace.

3. Conclusion

For many years, Nippon Steel has been developing mathematical models of blast furnaces, which have helped analyze the conditions pertaining to blast furnace operations, formulate blast furnace operation policies, stabilize the blast furnace operations and lower the reducing agent ratio.

In the future, it is necessary to integrate a multitude of models and to develop a total blast furnace visualization system. Developing non-steady state models, three-dimensional models, and discrete models of solid particle behavior are also future tasks.

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