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Advanced Technologies for Blast Furnace Life Extension

Kaoru NAKANO* Yutaka UJISAWA
Takanobu INADA Atsuhiro OBOSO
Kenji KATAYAMA

Abstract

Since blast furnace is a core process of steel mills, blast furnace repair requires a long repair period after blow-out and a large amount of money, which has a great impact on management. Extending blast furnace lives has been a major issue in order to provide more freedom in business decisions. On the other hand, mathematical blast furnace models, which have been developed since the 1970s, have improved prediction accuracy by repeating operation designs and analyses with data obtained over many years and extended these functions including analyses of the stress field in a blast furnace and erosion of hearth refractories. This paper outlines the mathematical blast furnace models and describes the technologies for blast furnace life extension and these applications to the next blast furnace designs.

1. Introduction

The blast furnace is a core process in steel works and is crucial equipment in determining the scale of the business operation of steel works. Blast furnace repair requires a long repair period after the blow-out and a large amount of money, and therefore, imposes a great load on management. The extension of the blast furnace life, which was about 5–10 years in the early 1970s, was a crucial issue in providing greater freedom in making business decisions.

The instrumentational information to grasp the in-furnace states is highly limited. Therefore, since the 1970s, Nippon Steel Corporation has developed blast furnace mathematical models to predict and analyze the phenomena in a blast furnace, and to give appropriate values to operation parameters for operation guidance (such guidance being hereinafter referred to as operation design). During the process of the development, the prediction accuracy has been improved by repeating the prediction, operation design and the operation analysis regarding the phenomena in a blast furnace by using the blast furnace mathematical models, corresponding to the changes in the operation conditions such as the increased ratio of pulverized coal injection and oxygen-enriched blasting. Furthermore, along with the improvement in the numerical computation capability, the blast furnace mathematical models became 3D from 1D, and the function was further sophisticated to cope with not only the phenomena of fluidity, heat transmission and reaction, but also the analyses of the stress of the BF packed bed and the hearth refractory erosion.

Thus, owing to the enhanced accuracies and the sophisticated functions of the blast furnace mathematical models thus far developed, the blast furnace mathematical models are now being applied not only to the conventional blast furnace design parameters, but also to a wider range covering the BF emptying operation design for stave cooler exchange and hearth refractory protection operation design. As a result thereof, the Wakayama No. 4 Blast Furnace which was designed for an operation life of seven years and was blown-in in 1982 was blown-out in July 2009, establishing the then world record of twenty-seven years and four months of continuous operation. Furthermore, the Wakayama No. 5 Blast Furnace which was blown-in in February 1988 achieved the world record of thirty years and eleven months of continuous operation when it was blown-out in January 2019.

In the meantime, the furnace shape and the hearth structure of the next generation blast furnace used to be designed based on the empirical information. However, the blast furnace mathematical models, the functions of which have been sophisticated by interacting with the actual blast furnace data during the development of the blast furnace life extension technologies, are now being applied. The currently operated Blast Furnaces of the Kokura No. 2 with a furnace volume of 2150 m^3, the Kashima No. 1 and No. 3 with a furnace volume of 5370 m^3 and the Wakayama No. 1 and No. 2 with a furnace volume of 3700 m^3 were designed from the theoretical viewpoint. All these blast furnaces are designed for a life span of twenty-five years or longer from blow-in.

* Chief Researcher, Ironmaking Research Lab., Process Research Laboratories
20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511

This article outlines the blast furnace mathematical models, and describes the development of the blast furnace life extension technologies, the blast furnace shape design and the hearth structure design by using the blast furnace mathematical models.

2. Progress of Research and Development

The progress of the research and development is shown in **Fig. 1**. The development of the blast furnace mathematical models was started in the early 1970s, and in 1974, the blast furnace mathematical models (one-dimensional steady model) exclusively developed by our own company were completed. Furthermore, to cope with the in-furnace non-steady states in a production blast furnace operation, non-steady blast furnace mathematical models were developed solely by our own company. In 1987, for the planning and the execution of the non-steady operation for the stave cooler exchange, one-dimensional non-steady blast furnace mathematical models were utilized. Thereafter, the blast furnace operation simulation models were used for such purposes as operation efficiency improvement and hearth refractory protection, and at the same time, their accuracy and practicability were enhanced through the interac-

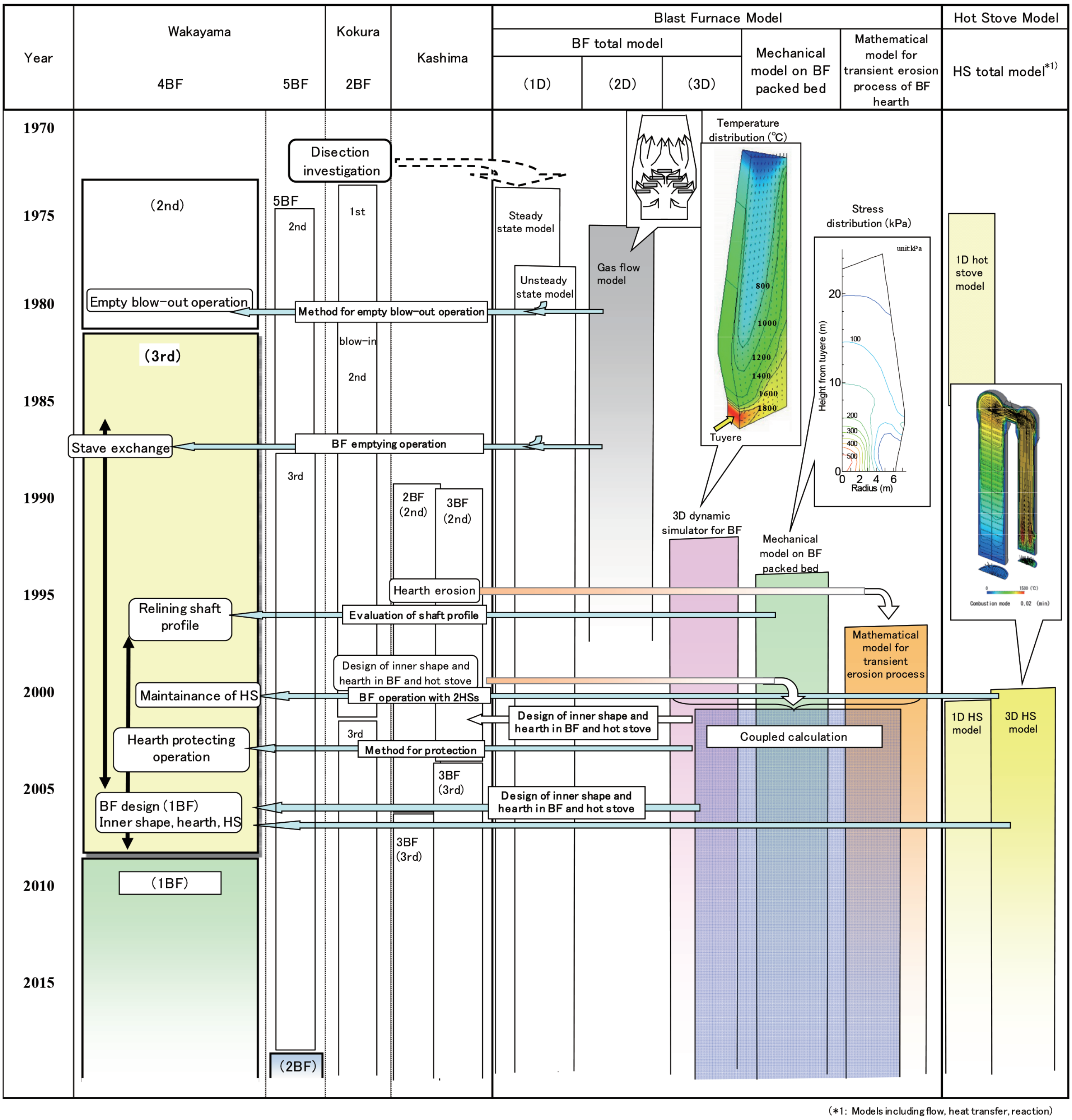

Fig. 1 Progress of technologies for blast furnace life extension and mathematical blast furnace model

tion with the diverse actual operation data. Such simulation models were advanced to the 3D non-steady blast furnace mathematical models (hereinafter referred to as the “3D dynamic simulator for BF”) that are capable of estimating the in-furnace distribution state in the directions of height, radius and circumference.

In addition, in order to evaluate the stability of the in-furnace material flow, which was impossible by the conventional technologies, the BF packed bed stress field estimation model (hereinafter referred to as the “Mechanical model on BF packed bed”) was completed in 1995, which is the first of its kind in the world that can estimate the burden descend and the stress distribution of the burden by assuming the BF packed bed as an elastic-plastic body. With the development of such varied mathematical models, the unrecognizable in-furnace state of a blast furnace that is considered to be a huge black-box-like reactor vessel has been quantified, and the quantitative estimations of the non-steady operation required for the equipment maintenance represented by the stave cooler exchange and the operating condition that suppresses the erosion of the hearth refractories have been realized.

Furthermore, by the integrated use of the 3D dynamic simulator for BF, the Mechanical model on the BF packed bed, and the hearth molten pig iron (molten pig being hereinafter referred to as hot metal) flow and hearth refractory erosion estimation models (hereinafter referred to as the “Mathematical model for the transient erosion process of the BF hearth”), the blast furnace mathematical models have been advanced to the level where they can provide guidelines for the designs of the shape of a blast furnace with high operation efficiency and high stability, and the hearth structure having a high resistance to the hearth refractory erosion.

3. Development of Blast Furnace Mathematical Models

In **Fig. 2**, the phenomena in a blast furnace and the developed blast furnace models are shown. In these models, the estimation method of the reaction rate, and the setting of correct numerical values for the parameters such as the characteristic values of heat and material transitions that govern the accuracies of the theoretical estimation when using mathematical models are crucial in determining the practical usability value of the models. Therefore, in these models, incessant development and improvement efforts have been made for a long period of time based not only on laboratory base experiments, but also by comparing and verifying the model data with the measured data obtained from actually operating blast furnaces. Key models that play important roles in the blast furnace life extension technologies are outlined hereunder.

3.1 3D dynamic simulator for BF

As shown in **Fig. 3**, the 3D dynamic simulator for BF[1)] is the model that enables the 3D recognition of the moment by moment non-steadily changing compositions, temperature distributions and the states of flow in the gaseous, liquid and solid phases. The blast

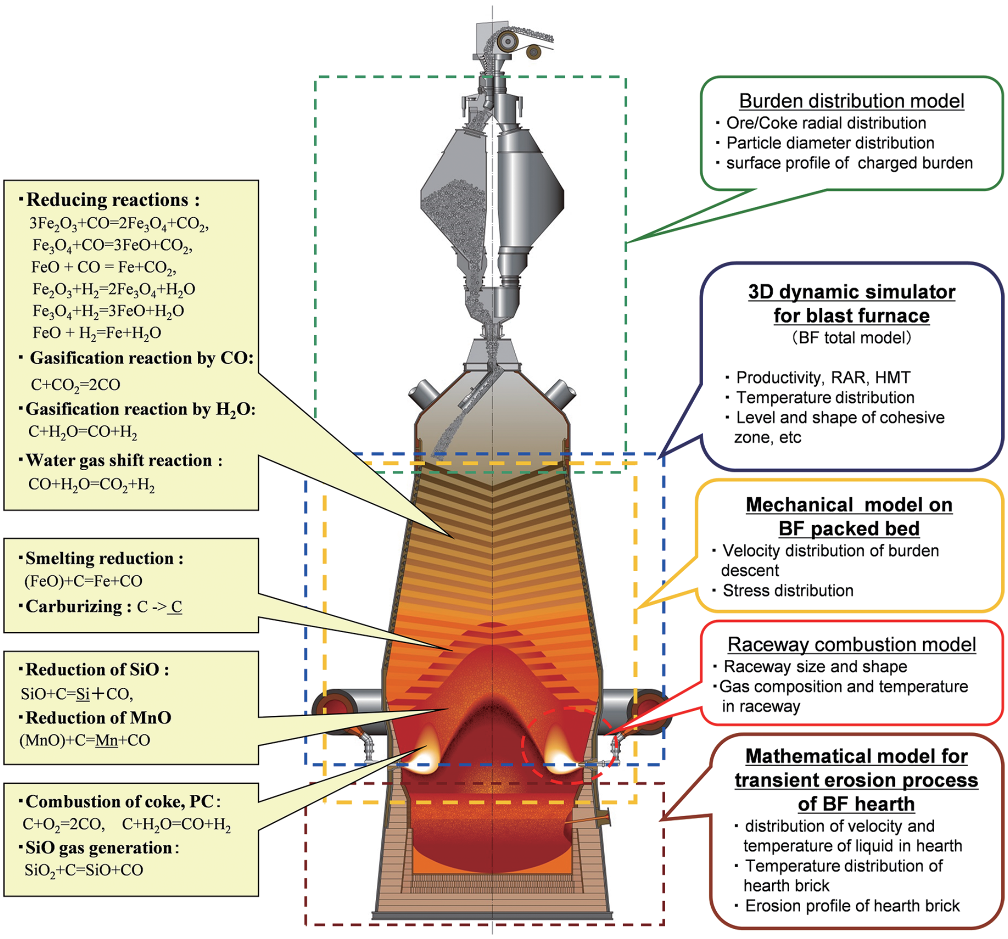

Fig. 2 Phenomena in blast furnace and mathematical models

furnace inner space is divided into minute regions. In each minute region, simultaneous partial differential equations consisting of balance equations with respect to material, energy and momentum in the gaseous, liquid and three solid phases are developed, and solved for numerical solution.

As an example of calculations by the models, in **Fig. 4**, the spatial distributions of the in-furnace state variables (from left to right: gas flow and temperature, solid flow and temperature, liquid flow and temperature, CO concentration, coke particle diameter and the rate of coke gasification) are shown. In **Fig. 5**, the calculation result of the transition of the solid temperature in a blast furnace after blow-in and start-up is shown. Either example shows the possibility of estimating the in-furnace state by providing the blast furnace operation initial condition (states of in-furnace burden, temperature distribution and so forth) and the boundary condition (charged burden distribution, blasting condition) to the blast furnace mathematical models.

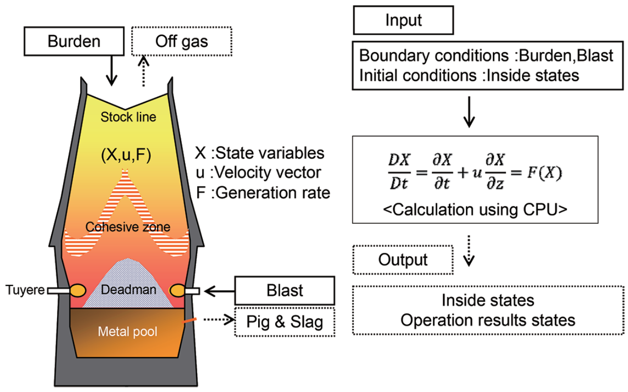

Fig. 3 Outline of 3D dynamic simulator for blast furnace

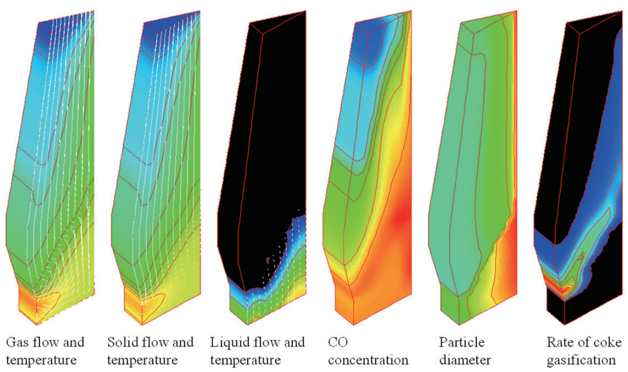

Fig. 4 In-furnace states calculated with the 3D dynamic simulator for blast furnace

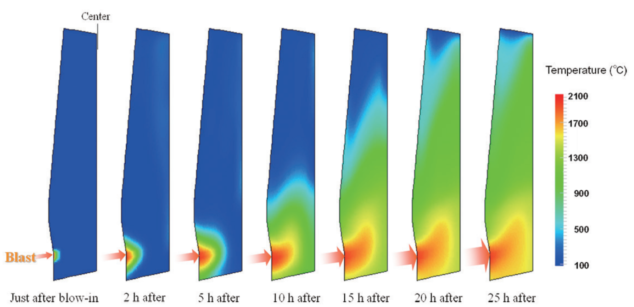

Fig. 5 Transition of solid temperature in a blast furnace after blow-in calculated with the 3D dynamic simulator for blast furnace

3.2 Mechanical model on BF packed bed

The inside of a blast furnace is packed by the moving bed consisting of iron ore and coke. Abnormality in the descent of the burden and the abnormal phenomenon of the gas flow are considered to be caused by the imbalance of forces occurring in the packed bed in the blast furnace. However, the conventional technologies failed to estimate these phenomena correctly as the technologies dealt with the in-furnace material flow approximately as that of a fluid, and this was an obstruction to estimating the in-furnace flow theoretically.

Regarding this subject, it was shown that, by assuming the in-furnace packed bed as an elastic-plastic body, the results obtained in the fundamental experiments and from measurement results obtained from the actually running blast furnaces are well explicable[2–4], wherein the Drucker-Prager formula generally used for the soil mechanics is employed for the yielding condition since the in-furnace packed bed consists of the particles of coke, sintered ore and so forth.

The in-furnace packed bed descends by gravity due to the disappearances of the coke in front of tuyeres by combustion and the ore in the cohesive zone. As shown in **Fig. 6**, while descending, the in-furnace packed bed is subject to the wall friction and the resistance to the gas that flows through in the furnace.[5] Furthermore, at its bottom end, the in-furnace packed bed is also exerted by the buoyancy from the hot metal and the molten slag existing in the hearth. The Mechanical model on the BF packed bed based on the assumption that the in-furnace packed bed descending under these forces follows the constitutive equation of an elastic-plastic body has enabled the highly accurate estimation and evaluation of the state of the descent and the stress distribution of the in-furnace packed bed.

Figure 7 shows the normal stresses to the wall obtained from the entire circumference 1/20 model experiment, and **Fig. 8** shows the comparison of the vertical stresses on the bottom obtained from the experiment and the calculation result. Changes of bottom stresses in the cases of with or without burden descent and with and without gas flow are quantitatively and accurately estimated. **Figure 9** shows the relationship between the charged burden level and the vertical stress distribution during the course of charging before

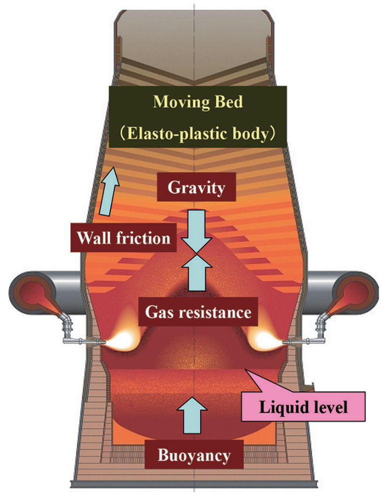

Fig. 6 Forces acting on moving bed in a blast furnace

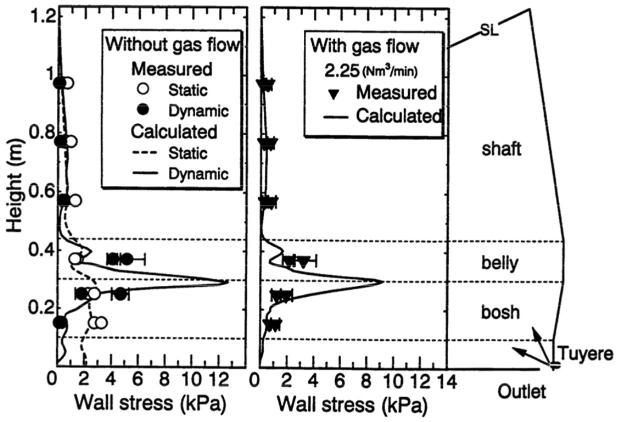

Fig. 7 Comparison of normal stresses on the wall between calculated results by the mechanical model on BF packed bed and measured results (1/20 cold model experiment)

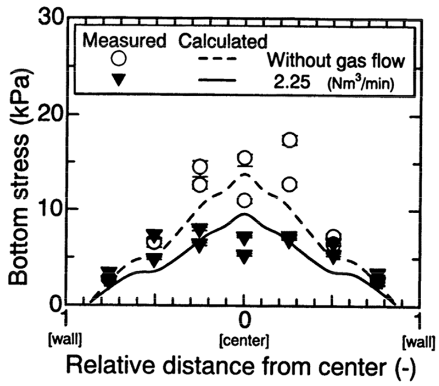

Fig. 8 Comparison of normal stresses on the bottom between calculated results by the mechanical model on BF packed bed and measured results (1/20 cold model experiment)

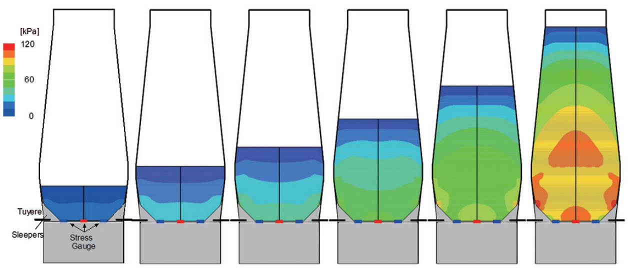

Fig. 9 Vertical stress distribution calculated by the mechanical model on BF packed bed during filling raw materials in Kokura 2BF

blow-in in the Kokura No. 2 Blast Furnace, and in **Fig. 10**, the comparison of the measured result and the calculated result of the bottom vertical stresses at the same time is shown. The Mechanical model on the BF packed bed is able to estimate the vertical stresses accurately even in the production blast furnace.

3.3 Mathematical model for transient erosion process of BF hearth

Since the blast furnace in-hearth states are difficult to capture directly except their refractory temperature by direct measurement, the estimation based on theory is important, and is the sole means.

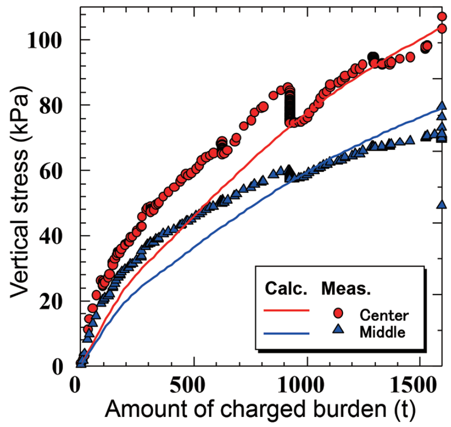

Fig. 10 Comparison of calculated vertical stress by the mechanical model on BF packed bed with measured one during filling raw materials in Kokura 2BF

Therefore, the Mathematical model for the transient erosion process of the BF hearth was developed to estimate the hot metal flow in the hearth, and to estimate the temperature distributions of hearth and hearth refractories, and further, to estimate the transient hearth refractory erosion.[6, 7]

Figure 11 shows the calculation flow of the Mathematical model for the transient erosion process of the BF hearth. The final refractory erosion state is obtained in the following manner. First, the following are the input conditions: first the radial distributions of the amount and the temperature of the hot metal and the molten slag dripping to the hearth and the particle diameter and the void fraction of the deadman coke, both calculated from the aforementioned 3D dynamic simulator for BF, and second, the deadman coke sinking level for the hearth and its bottom end profile calculated by the Mechanical model on the BF packed bed as shown in **Fig. 12**. Next, the liquid flow in the hearth and the heat transfer phenomena to the hearth refractories are analyzed. The refractory part susceptible to the eroding condition is eroded by the model, and the cycle of calculating the flow, heat transfer and the refractory erosion is repeated until the final erosion state is obtained.

By core-sampling the residual refractories and the in-furnace residual material after blow-out (dissection survey), and by comparing the analysis result with the actual state of the erosion and verifying thereby, models having higher accuracies could have been developed. **Figure 13** shows the comparisons of the model calculation result with the actually measured remaining refractory thickness obtained by the boring survey conducted at the dismantling of the hearth of the Wakayama No. 4 Blast Furnace and the Kokura No. 2 Blast Furnace, which prove that the erosion is simulated with high accuracy.[5, 8)]

4. Development of Blast Furnace Life Extension Technologies

4.1 Development of hearth refractory erosion suppressing technologies

As a result of the sensitivity analysis conducted for various operation conditions by using the developed models regarding the hearth structure of the Wakayama No. 4 Blast Furnace, it was suggested that the sinking level of the deadman coke exerts a significant influence upon the erosion of the hearth refractories. **Figure 14** shows the influence of the deadman coke sinking level in the hearth

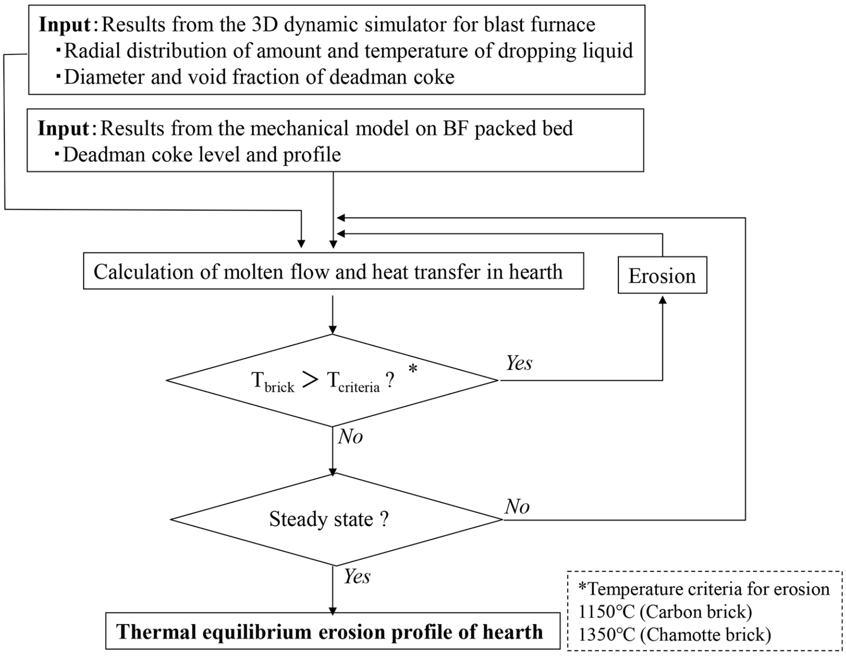

Fig. 11 Flowchart of the mathematical model for transient erosion process of blast furnace hearth

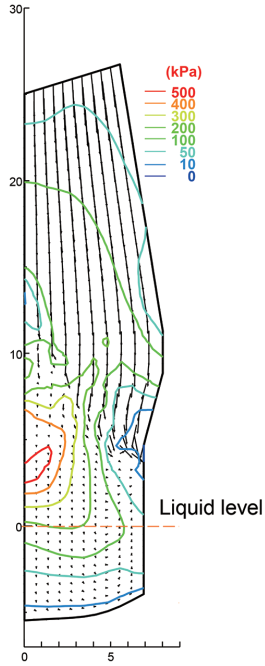

Fig. 12 Sinking level and its shape calculated by the mechanical model on BF packed bed

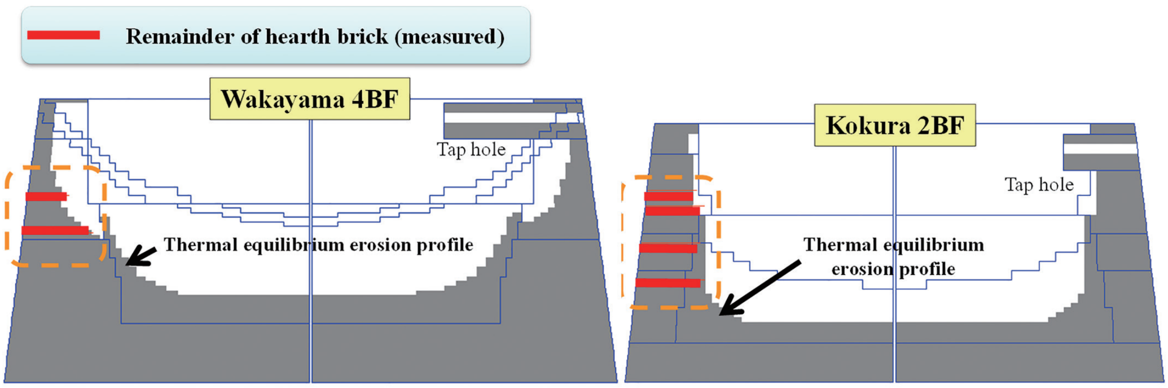

Fig. 13 Comparison of erosion profile of hearth between calculated results by the mathematical model for transient erosion process of BF and measured ones

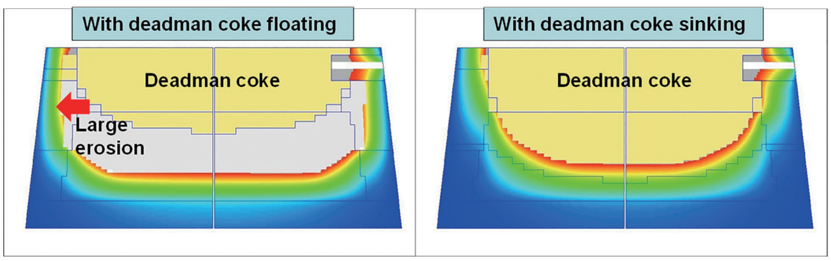

Fig. 14 Influence of deadman coke level in hearth on erosion of hearth refractories

on the erosion of hearth refractories.[5] In the case that the deadman coke floats, a coke-free layer (a region without coke) appears on the side wall wherein the hot metal flow is intensified, and it is considered that, as a result thereof, the heat load increases, and the refractory erosion progresses.

Then, the deadman coke sinking level (the distance between the tap hole level and the bottom end of the deadman coke) obtained by the one dimensional simplified calculation of the mechanics of the balance of the BF packed bed is taken as an index, and the relationship between the index and the actual furnace hearth refractory tem-

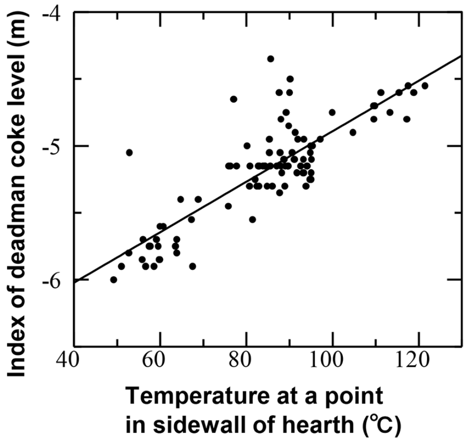

Fig. 15 Relation between index of deadman coke level and temperature of sidewall of hearth

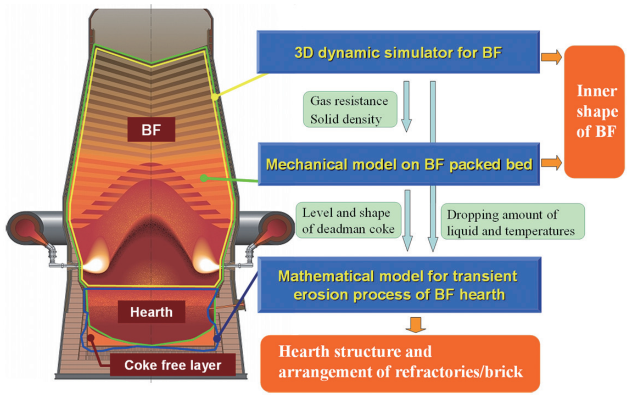

Fig. 17 Technologies of design for blast furnace with combining mathematical blast furnace models

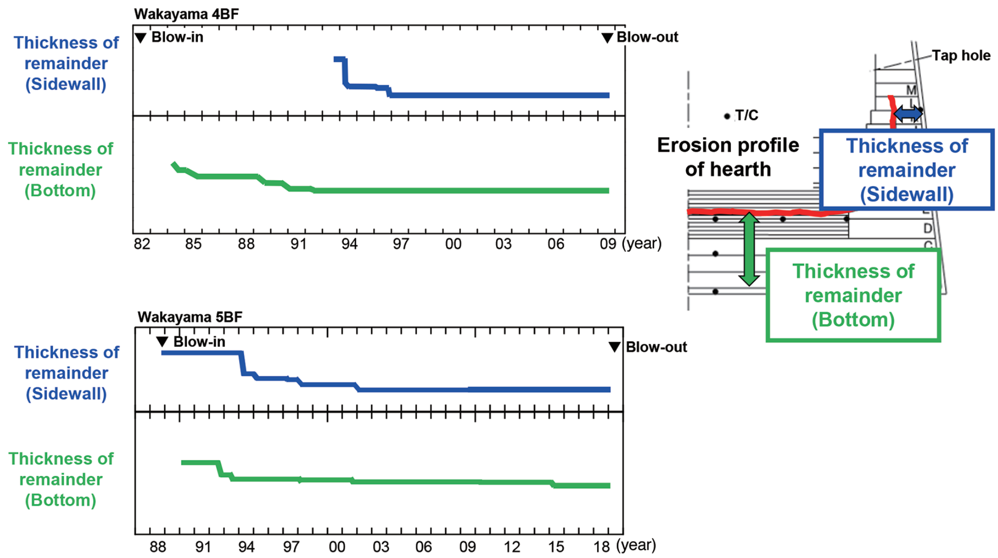

Fig. 16 Transition of maximum erosion of hearth refractories estimated by measured temperature of hearth in Wakayama 4BF and 5BF

perature is shown in **Fig. 15**.[9, 10] A good correlation with the actual furnace operation result is confirmed, and it is proved that the deadman coke sinking level is a significant factor that influences the hearth refractory temperature.

Based on this information and by using the abovementioned index as a control parameter, and by controlling this index in the ordinary operation design and the daily operation control (by changing the blast rate, oxygen blasting ratio, coke ratio and the like), a technology to control the heat load to the hearth has been established.

As a result thereof, as shown in **Fig. 16**, in the Wakayama No. 4 Blast Furnace, with respect to the progress of the hearth erosion in the maximum erosion progress direction until the blow-out in 2009, the progress of the erosion of the hearth sidewall was suppressed after 1996, and the progress of the erosion of the hearth bottom was suppressed after 1992. In addition, similarly in the Wakayama No. 5 Blast Furnace, the progress of large erosion of the sidewall and the bottom was suppressed up to its blow-out in 2019.

5. Application to Blast Furnace Design

By the integrated application of the 3D dynamic simulator for BF, the Mechanical model on the BF packed bed and the Mathematical model for the transient erosion process of the BF hearth as shown in **Fig. 17**,[5] the design guidance has been provided to the blast furnace shape design to realize high operation efficiency and stabilized operation, and to the hearth structure design to provide high erosion resistance to hearth refractories. The blast furnace shape design and the hearth structure design based on the blast furnace mathematical models are described hereunder.

5.1 Blast furnace design

The inner shape of a blast furnace (blast furnace shape) exerts a significant influence upon the blast furnace operation, and is a crucial subject in the design of a blast furnace. As shown in **Fig. 18**, in the blast furnace shape design of the Blast Furnaces of Kokura, Kashima and Wakayama, under the management condition of production amount and spatial restriction, two independent parameters (bosh angle and belly height) had to be determined. Contrarily to the past blast furnace design method based on empirical rules, as shown in **Fig. 19**,[5] by using the blast furnace mathematical models, the evaluation of the stability of the blast furnace with respect to the in-furnace permeability and fluidization (channeling) was conducted, and the result was provided as the guideline for the blast furnace shape design.[11, 12)]

In particular, regarding the fluidization (channeling), by using the Mechanical model on the BF packed bed, the channeling factor (CF) was defined as Form (1), and the stability was evaluated.

$$\text{Channeling factor (CF)} = \frac{\Delta P}{\sigma_{yy}} \qquad (1)$$

where ΔP: pressure difference between the furnace top pressure and the pressures within the BF packed bed, and σ_{yy}: vertical stresses within the BF packed bed. The CF value exceeding 1.0 means gas channeling theoretically, and therefore, CF needs to be below 1.0 in the entire region except the raceway region.

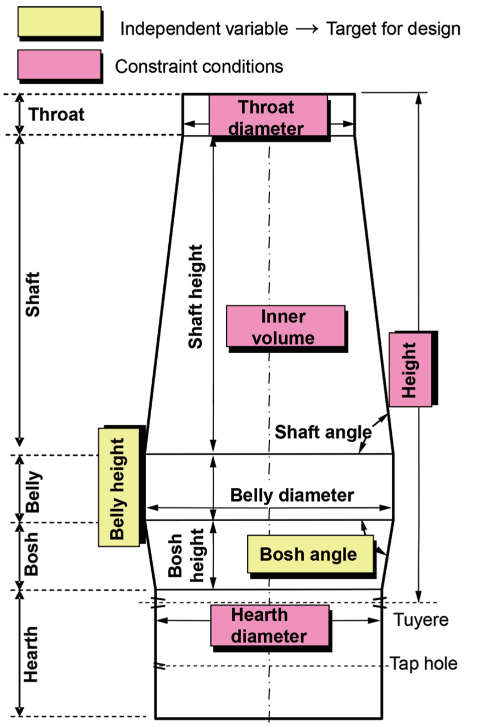

Fig. 18 Target valuables for design of inner shape of blast furnace

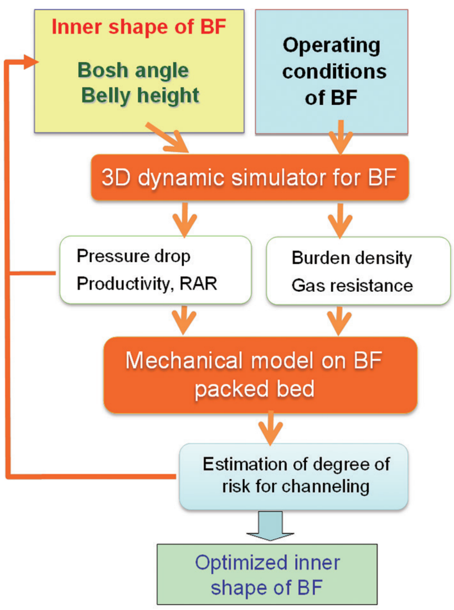

Fig. 19 Flowchart of design for inner shape of blast furnace with mathematical blast furnace models

Figure 20 shows the effect of the furnace shape on the in-furnace vertical stresses. The in-furnace vertical stresses change depending on the furnace shape. **Figure 21** shows the effect of the furnace shape on the in-furnace CF. Depending on the furnace shape, CFs in the neighborhoods of the shaft section wall (a) and the belly section wall (b) change in particular. **Figure 22** shows the relationship between the belly height and the peak value of CF in the neighborhood of a wall.[5)] As the belly height increases, CF in the neighborhood of the shaft section wall CF(a) decreases, while CF in the neighborhood of the belly section wall CF(b) increases when the belly height exceeds 1.5 m.

Figure 23 shows the relationship between the bosh angle and the pressure drop.[5)] It shows that the pressure drop is smallest in the neighborhood of the bosh angle of 79 degrees. Thus, by conducting

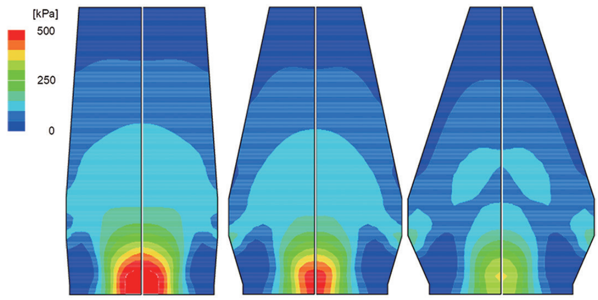

Fig. 20 Influence of inner shape of blast furnace on vertical stress

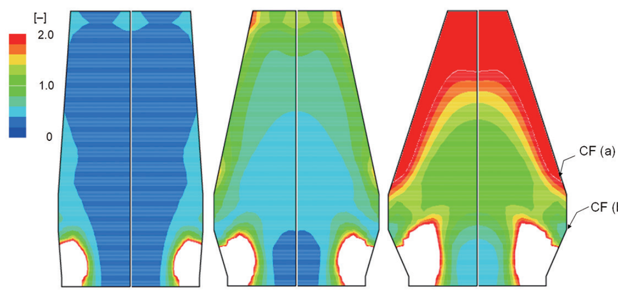

Fig. 21 Influence of inner shape of blast furnace on CF

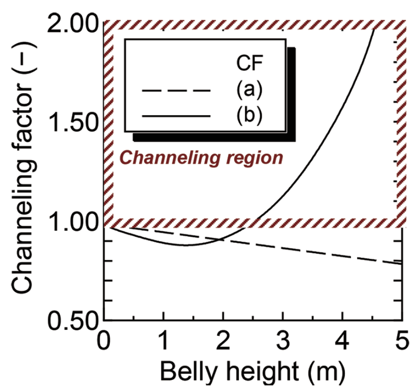

Fig. 22 Relation between belly height and peak values of channeling factor at wall

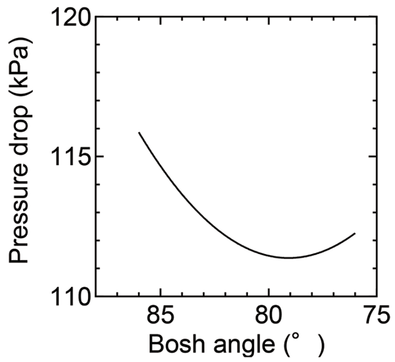

Fig. 23 Relation between bosh angle and pressure drop

simulations for various furnace shapes, the furnace shape with the low in-furnace pressure drop and with low danger of channeling is adopted (low probability of material fluidization occurrence, and excellent in in-furnace material flow stability).

5.2 Hearth refractory structure design

The blast furnace hearth refractories are unreplaceable in the daily operation even with the modern technologies. The design of a hearth of a new blast furnace including the refractories layout is as important as the design of the blast furnace shape. Upon the study on the design of the hearth structure of a new blast furnace, as described earlier, the hearth design needs to be scrutinized and evaluated; first based on the sinking level and the bottom end profile of the deadman coke obtained from the dripping hot metal quantity distribution and the temperature distribution thereof calculated by the 3D dynamic simulator for BF and the Mechanical model on the BF packed bed, and second, by estimating the erosion profile of the hearth refractories by providing the subject refractory layout and the hearth structure condition to the Mathematical model for the transient erosion process of the BF hearth.

In **Fig. 24**, the effect of the depth of the hearth on the hearth refractory erosion is shown.[5] It is suggested that securing the sufficient depth of the hearth in the initial stage is important, and as shown in **Fig. 25**, the hearth depths of the Blast Furnaces of Wakayama, Kokura and Kashima, all blown-in in and after 2002, are designed to be higher than those of the past Blast Furnaces.

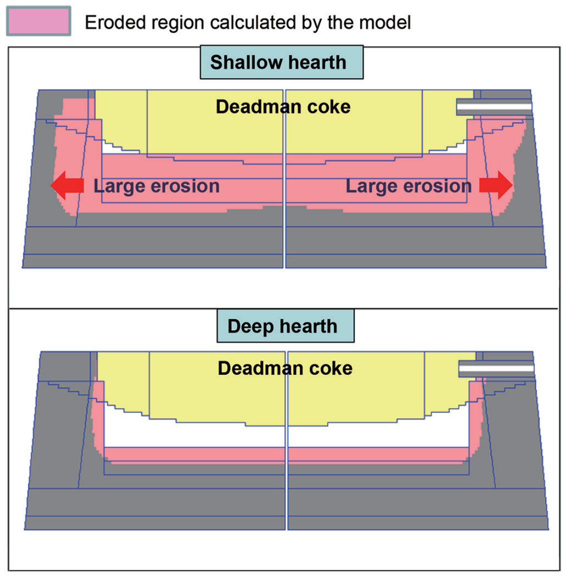

Fig. 24 Effect of hearth depth on erosion of hearth refractories

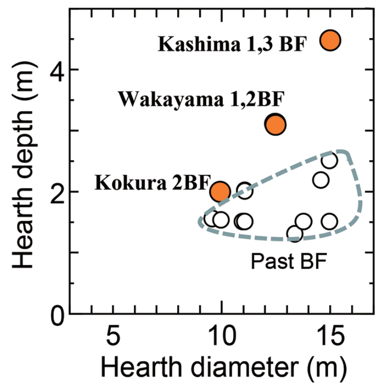

Fig. 25 Relation between hearth diameter and hearth depth of blast furnace in Wakayama, Kokura and Kashima

6. Conclusion

The Wakayama No. 4 Blast Furnace that was originally designed for an operating life of seven years maintained operation for longer than twenty-seven years (blown-out on the 10 001st day), establishing the then world record in terms of continuous operation life. Furthermore, the Wakayama No. 5 Blast Furnace that was blown-in in February 1988 achieved the world-record long continuous operation days of 11 289 (thirty years and eleven months) until its blow-out in January 2019. The element technologies of blast furnace life extension established in the Wakayama No. 4 and 5 Blast Furnaces were applied not only to our own company's blast furnaces, but also to other steel companies' blast furnaces through technical cooperation and/or technical support, contributing greatly to their blast furnace life extension.

The blast furnace mathematical models, well-advanced in terms of accuracy and practical usability realized by incorporating the expertize from the actual operation, have been applied not only to the life extension of the existing blast furnaces, but also to the newly constructed blast furnaces, and the Kashima No. 1 and No. 3 Blast Furnaces and the Wakayama No. 1 and 2 Blast Furnaces have been designed and constructed for a life of over twenty-five years.

Hereinafter, we are determined to continue to make efforts to enhance the accuracy of the blast furnace mathematical models by interacting with the actual furnace operation data, intending to further stabilize the blast furnace operation, enhance the operation efficiency and suppress the carbon dioxide gas emission, and to further sophisticate the blast furnace life extension technologies and the new blast furnace design technologies.

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Kaoru NAKANO
Chief Researcher
Ironmaking Research Lab.
Process Research Laboratories
20-1 Shintomi, Futtsu City, Chiba Pref. 293-8511

Yutaka UJISAWA
Dr. Environmental Studies
General Manager, COURSE50 Sub-project Leader
R & D Planning Div.

Takanobu INADA
Dr. Eng.
R & D Planning Div.

Atsuhiro OBOSO
General Manager, Head of Dept.
Ironmaking Technical Dept.
Ironmaking Div.
Wakayama Works

Kenji KATAYAMA
General Manager, Head of Div.
Ironmaking Div.
Oita Works