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Process Analysis for Blast Furnaces by the Discrete Element Method†

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Abstract:

Discrete element method (DEM) calculation revealed the following: A packed bed in a blast furnace is supported by the formation of a network structure by particles receiving heavy stress. And the stress at the contact point of coke in the network can exceed the compressive strength. Shaft angle strongly affects solid flow and strength of stress in a blast furnace. On the assumption that the particle size of coke in molten pig iron decreases due to carbon dissolution, a coke powder layer is formed in the stagnant zone. The layer can protect the refractory of hearth against erosion, and its thickness is strongly affected by the depth of hearth and load of burden.

1. Introduction

With the increasing demand for reduced CO_2 gas emission in recent years, improvements in productivity and energy efficiency in steel works have become a social responsibility. Extremely strict requirements for CO_2 gas reduction are now placed on ironmaking, a process in which iron ore is reduced and melted by consuming large amounts of coal, and in which energy is supplied as combustible byproduct gases to other processes in the steel works. Ironmaking in a blast furnace takes place by charging sinter (in the form of agglomerated iron) ore and coke (in the form of agglomerated coal) from the top of the furnace, while blowing hot blast into the furnace bottom. High energy efficiency and productivity are achieved in the process by a countercurrent moving bed reaction. There now is an orientation toward reduced agent rate (RAR) operation and increased hot metal production with a new generation of large-scale blast furnaces with inner volumes exceeding 5 500 m^3. There have also been important technical developments, including high-pressure operation, oxygen-enriched hot blast blowing techniques, blowing of reducing agents through the tuyeres, and so on. To achieve further improvements, however, it will be indispensable to quantitatively grasp the limiting phenomena in blast furnace operation and to develop technologies for avoiding the limitations.

Studies using continuum models, discrete models, or combinations of the two seem to be necessary to succeed in elucidating the formation mechanisms behind the limiting phenomena and quantitatively grasping ways to minimize the limitations. Discrete models, however, have only been recently applied to blast furnaces (compared to continuum models), and the calculations by discrete models do not apply the blast furnace as a whole. Indeed, the discrete model approach is still at the stage of partial modeling and focuses on only some phenomena. In this report we describe examples of application of discrete models to the blast furnace to date, mainly at JFE Steel, and discuss issues in the application of the discrete element method.

2. Application of the Discrete Element Method to Blast Furnaces

The discrete element method (DEM) was introduced in civil engineering by Cundall et al. in the 1970s. Because DEM faithfully reproduces the characteristics of powder behavior, it has become one of the representative powder simulation methods covering multi phase

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flows[1]. Cognizant that the raw materials used in ironmaking are granular bodies, Tanaka et al. applied DEM to calculations on gravitational discharge from the hopper, blast furnace deadman formation, furnace-top burden segregation, the behavior of materials in the raceway, etc. in steel industry studies of the 1980s[2–6]. Since the 1990s, the applications of DEM have expanded to studies on the ironmaking process as a whole, including studies on the sintering process (Kato et al.)[7] and the pushing process (Ariyama et al.)[8]. Since the above-mentioned work by Tanaka et al., DEM simulation techniques have been developed to simulate furnace-top raw material charging[9], segregation at the burden surface[10], burden descent and deadman formation[11,12], coke free space formation[13], rotation/extinction of particles in the raceway[14,15], etc. These phenomena can also be reproduced by simulations of a continuum. The discrete element method has a distinctive advantage, as it can be used to calculate the free surface shape of a granular body, the shape of the stagnant region, particle segregation, and a stress network structure. To estimate the layer profile by continuum model, for example, we need to adjust the surface function and arbitrary constants based on model experiments. For the shape of the deadman, we need to assume the deadman shape itself or tune the variables. Where segregation phenomena are concerned, the segregation coefficient must be adjusted by experiments or investigations of an actual blast furnace. A continuum model is adequate for practical applications, for example, in reproducing actual blast furnace phenomena in steady-state operation and in operation design. The results, however, will inevitably be approximations of the motions of granular bodies, as the physical properties of a continuum are introduced into calculations on the granular-body interaction, a behavior which by nature cannot be explained by fluid dynamics. And because the stress network structure supporting the packed structure of granular bodies is a discontinuous phenomenon, we can presume that reproduction by a continuum simulation will be extremely difficult.

Because the DEM has features not found in the simulations of continuums, as mentioned above, the application range continues to expand in spite of the limited applicability of the method to partial models of the blast furnace. The following chapters will present examples of DEM analyses of blast furnace phenomena conducted at JFE Steel.

To shorten the computation time, we used two simulations (the whole furnace, the hearth) selectively. The simulation conditions and geometries are shown in **Table 1** and **Fig. 1**, (a) and (b), respectively. The effects

Table 1 Simulation conditions of analysis of blast furnace based on DEM

	Whole blast furnace	Hearth
Diameter, d_p (m)	0.2	0.1*
Particle density, ρ_S (kg/m^3)	1 000	1 000
Liquid density, ρ_L (kg/m^3)	6 700	6 700
Particle number, N	30 000	30 000
Poisson's ratio, υ	0.2	0.2
Restitution coefficient, e	0.46	0.46
Sliding friction coefficient, μ_s	0.7	0.7
Rolling friction coefficient, μ_r	0.06 d_p	0.075 d_p
Normal stiffness, k_n	$m\pi^2/(10\Delta t)^2$	$m\pi^2/(10\Delta t)^2$
Shear stiffness, k_t	$k_n/[2(1+\upsilon)]$	$k_n/[2(1+\upsilon)]$
Time step, Δt (s)	10^{-4}	10^{-4}
Discharging rate at raceway (s^{-1})	500	
Discharging rate at hearth (s^{-1})	0, 33, 50, 143	1 300**

* Particle diameter is decreased in proportion to residence time under liquid level: d_p=Max (0.1−0.01t, 0.06)
** Correspond to 0.1 m diameter particle volume

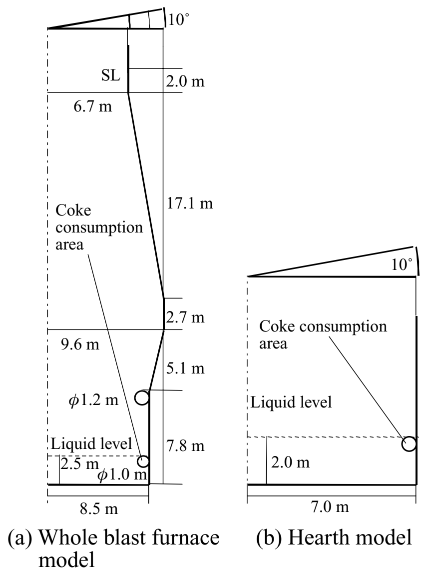

Fig. 1 Geometries used in DEM simulation of blast furnace solid flow

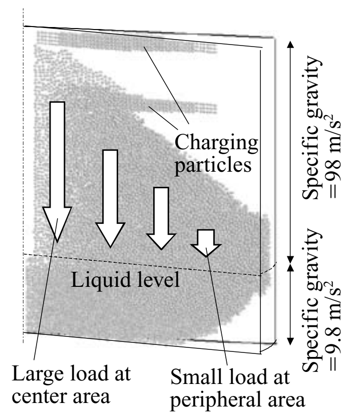

Fig. 2 Reproduce burden load distribution by particle piling and large gravity

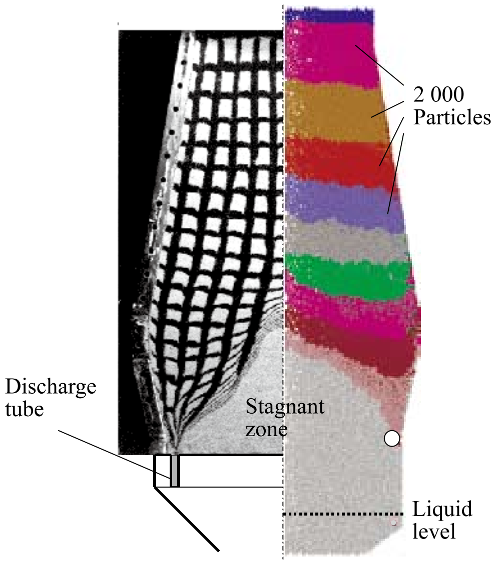

Fig. 3 Burden descending timeline and stagnant zone shape

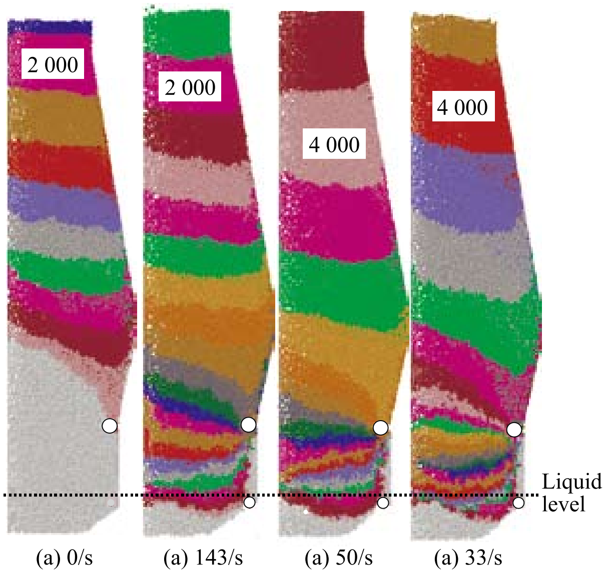

Fig. 4 Effect of hearth coke consumption on stagnant zone renewal (Particle colors are changed every certain number shown in the figure.)

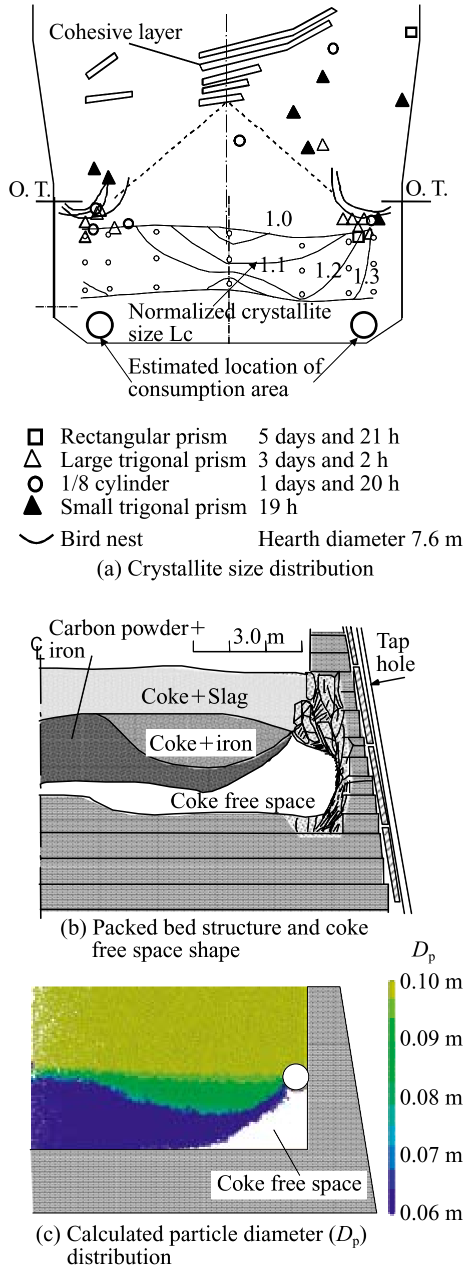

Fig. 5 Dissection analysis Results of No. 4 blast furnace, West Japan Works (Kurashiki)

of fluids (gas and liquid flows) were ignored in both simulations. In the hearth model, we assumed that coke is consumed in the peripheral area directly below the tuyeres via direct reduction by the FeO in the slag and carbon dissolution[16,17], thereby resulting in a gradual decrease in the particle size of the coke in the molten pig due to carbon dissolution. The load distribution on the hearth was reproduced by causing particles to be piled in the manner shown in **Fig. 2**.

Verification is indispensable in numerical simulations, including DEM. Simulation results obtained when particles are discharged from the raceway position are shown in **Fig. 3**, (a) and (b), as compared with the results of a scale-model burden descent experiment[18]. The calculated deadman volume (stagnant zone) and timeline profile show the same tendencies observed in the model experiment. Results of a simulation of the effect of hearth coke consumption on the renewal of the stagnant zone are presented in **Fig. 4**, (a) to (d). As shown here, the stagnant zone cannot be renewed without hearth coke consumption (Fig. 4, (a)). According to the calculated results, the intervals between the timelines in the hearth are narrow in the peripheral zone and center zone, and wide in the intermediate area (Fig. 4, (b) to (d)). **Figure 5**, (a) to (c) shows results of a dissection analysis of No. 4 BF, West Japan Works (Kurashiki), and calculated solid flows in the hearth. The features of the timelines by DEM simulation are similar to the crystallite size distribution (distribution of hearth coke graphitization (Fig. 5, (a)) in the dissected furnace. On the assumption that the particle size of coke in molten pig decreases due to carbon dissolution, as shown in Table 1, these results confirm that a coke powder zone like that observed in the dissected furnace is formed in the stagnant zone (Figs. 5, (b) and 5(c)).

3. Results and Discussion

The design of the blast furnace body is very important for the stability of the burden descent, a factor which itself is important for the stability of blast furnace operation and the furnace body life. An important factor in stable burden descent is the furnace profile, particularly the shaft angle. Scale-model experiments have shown that descent is more rapid in the furnace wall area than in the center when the shaft angle is small, whereas descent in the furnace wall area is delayed when the shaft angle is large[19]. Therefore, the authors used this DEM simulation to calculate the effect of the shaft angle on the burden descent. The results are shown in **Figs. 6**, (a) to 6(c). When the shaft angle is 75°, the descent in the wall area is clearly faster than that in the center. With an angle of 85°, on the other hand, the burden descent is delayed in the vicinity of the furnace wall. This is substantially in agreement with the results of our previous experimental research. The height of the deadman tends to decrease as the shaft angle increases. The load of the burden applied to the deadman increases as a result of an increase in the inner volume caused by increases in the shaft angle and furnace throat diameter, which in turn results in a decrease in the angle of the slip line. This pattern of effects seems to reflect the need for burden materials of higher strength in blast furnaces with large shaft angles. The shaft angle of blast furnaces now used in Japan ranges from 79° to 84°. Based on the simulation results described above, we estimate that a current shaft angle of around 80° is appropriate for obtaining a stable burden descent and degradation the pulverization of the burden materials.

Because the renewal of the stagnant zone in the blast furnace is slow and the permeability of the stagnant zone is low, a small deadman cross-sectional area is considered desirable. Because the deadman is an area enclosed by the raceway, an increase of the raceway depth is considered an effective means to reduce the deadman. The raceway depth can be increased by raising the blase speed at the tuyeres and moving the tuyere tip position toward the furnace center. Noting this, the authors used DEM to calculate the effect of moving the raceway position toward the furnace center. The calculation results are shown in **Figs. 7**, (a) and (b). As the figure shows, a change in calculated position for the end of the raceway from 1.2 m to 1.5 m toward the furnace center reduces the volume of the deadman by 18% and leads to the formation of a coke holdup zone at the bosh surface, a factor which can be expected to reduce the heat load. As these results clearly show, a deeper tuyere tip position in the furnace within the range where no melting or buck-

(a) Shaft angle: 75° (b) Shaft angle: 80° (c) Shaft angle: 85°

Fig. 6 Calculated effects of shaft angle on solid flow

(a) 1.2 m (b) 1.5 m

Fig. 7 Calculated effects of raceway position on dead man size by DEM

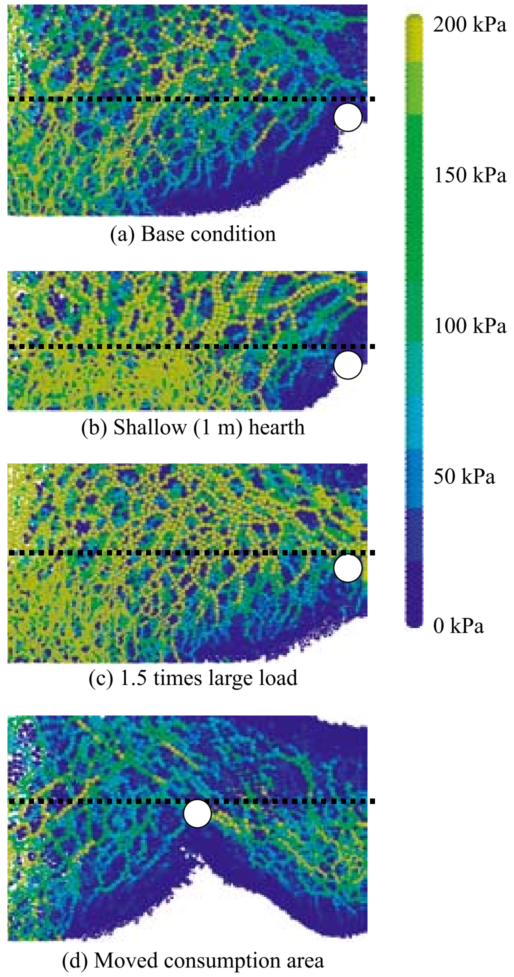

Fig. 8 Calculated result of stress field and coke free space shape in hearth

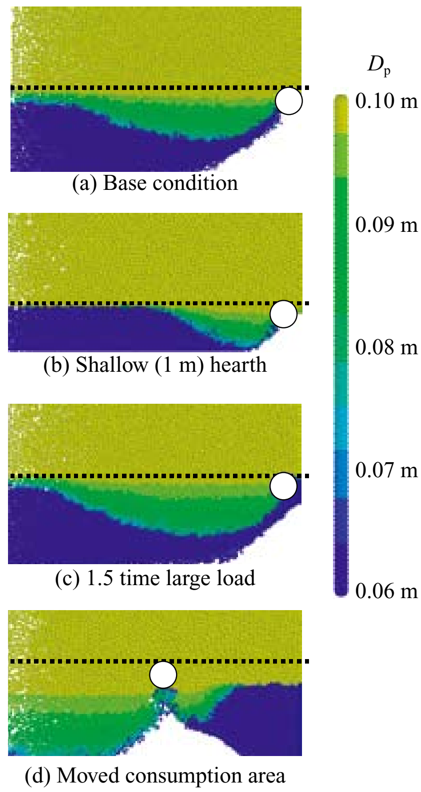

Fig. 9 Calculated result of coke diameter distribution in hearth

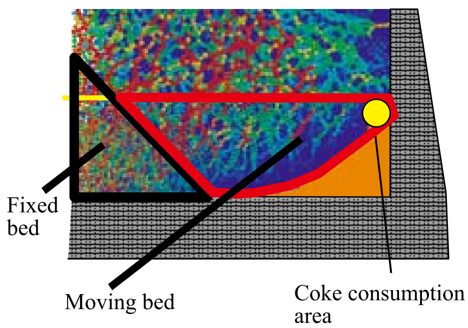

Fig. 10 Control methods to form thick coke powder zone

ling occur is desirable in terms of permeability and heat load reduction.

The packed structure (free space shape, coke particle size distribution) in the blast furnace hearth is important from the standpoints of stable casting and the prevention of hearth wear. While it is difficult to approximate a solid flow in a buoyant condition using a continuum model, it has become possible to calculate the free space shape and coke particle size distribution by applying DEM. We see, from Fig. 4, (a) to (d) that the hearth coke free space is formed in the corner parts of the hearth. This means that it is difficult to eliminate the free space by loading alone when the hearth is deeper (from the taphole to the hearth plate) than a certain predefined depth. For a more detailed study, the authors made calculations using the hearth model. The results are shown in Figs. 8, (a) to (d). Even when the hearth is shallow, the deadman and free space are not lifted, but are simply cut off by the hearth plate height (**Figs. 8**, (a) and (b)). The authors also observe that an increase in the burden load by as much 1.5 times will not extinguish the free space, as the stress network extending from the side walls and the hearth supports the packed bed (Fig. 8, (c)). When the position of coke consumption is an intermediate area in the furnace, the largest free space will appear directly under this area. Considering that similar results have been obtained in water model experiments conducted using wooden balls [13, 20, 21], we believe that the shape of the free space depends on the distribution of coke consumption rather than on stress distribution.

Figures 9, (a) to (d) shows the results of a calculation of the particle size distribution in steady-state operation. Due to a reduction of the coke particle size, coke with a long residence time forms a coke powder zone of the same shape as that found in the dissected blast furnace (Figs. 5 and 9, (a)). On a shallow hearth, however, the authors find that almost all of the coke is trapped, leading to a concentration of the coke renewal in the peripheral area (Fig. 9, (b)). This suggests that the erosion of the hearth wall refractories in shallow-hearth furnaces is accelerated by a concentration of hot metal flow (circumferential flow) in a relatively confined free space. Given that a large burden load will cause sinking of the deadman and the formation of a thicker coke powder zone (Fig. 9, (c), we know that erosion could be more easily avoided under a large burden load condition like that in high O/C (ratio of the charged ore weight to the coke weight), low pressure loss operation, as shown by the Deadman Sinking Index[22]. When the coke consumption position is at an intermediate position, the peripheral region is occupied by fine coke (Fig. 9, (d)). This suggests the possibility that casting conditions will deteriorate if Lo/Lc (the ratio of the ore layer thickness to the coke layer thickness)at lentermed zone becomes extremely large, as observed in an actual blast furnace using a tuyere probe[23]. Based on the simulation results described above, a method for forming a stable coke powder zone to protect the hearth is shown in **Fig. 10**. If the deadman is in contact with the hearth bottom plate, a strong load presses the conical region in the axial center of the furnace, restricting the movement of the deadman and interfering with the deadman's renewal. Other parts are gradually renewed by the supply of coke from above and the consumption of the coke at the periphery. An effective way to attain stable formation of a coke powder zone is to extend the renewal time of this moving bed. Increasing the volume of the moving bed and reducing the coke consumption rate in the peripheral area are conceivable as methods for achieving this. The moving bed volume can be increased by sinking the deadman via a high O/C operation or burden permeability improvement, or by reducing the volume of the conical fixed bed by designing a deeper hearth plate. Coke consumption in the peripheral area can be suppressed by reducing production or by shielding the tuyeres directly above the wear position.

4. Conclusions

Examples of DEM analysis of the phenomena in the blast furnace were presented. Calculation of the burden descent in the blast furnace, stress distribution, shape of the coke free space in the hearth, and the coke particle size distribution in the hearth has made it possible to evaluate the blast furnace equipment design, including the shaft angle, tuyere design, hearth plate depth, and so on. Faster and more accurate simulations will become possible with future improvements in computer performance and improvements in the DEM technique.

In addition to the general problems and limitations of FEM, on the other hand, there are still problems which are difficult to reproduce by DEM, either for technical reasons or due to the computational load. Prominent problems include wide-ranging particle size distributions and velocity distributions in the furnace, softening/cohesion phenomena, droplet-related phenomena, the segregation, mixing, destruction and degradation of irregularly shaped particles, multiparticle state, consumption in chemical reactions, and the like. As described in the introduction, the integration of a discrete model into a continuum model may become an important goal for the further application of DEM to the blast furnace.

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