STUDIES AND APPLICATIONS OF DISCRETE ELEMENT METHOD AGAINST BLAST FURNACE

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Abstract

Application of the discrete element method (DEM) to study of phenomena inside the blast furnace has expanded, including analysis of hopper discharge, burden profile, segregation at the burden surface, burden descent, raceway reaction, deadman shape, coke deterioration, and coke free space. This paper introduces the models based on DEM and applications at JFE Steel. Two mathematical models based on DEM have been developed to calculate solid flow and stress field in a blast furnace. Although the models do not count in drag force of liquid and gas, the results well agree with that of scale model experiment and dissection analysis. 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.

Key words: Blast furnace; Solid flow; Discrete element method; Coke.

ESTUDOS E APLICAÇÕES DO MÉTODO DOS ELEMENTOS DISCRETOS CONTRA ALTO-FORNO

Resumo

A aplicação do método dos elementos discretos (DEM) para estudar o fenômeno dentro do alto-forno tem se expandido, incluindo a análise da descarga da tremonha, perfil da carga, segregação na superfície da carga, caída da carga, reação na zona de combustão (raceway), forma do homem-motor, deterioração do coque e espaço livre do coque. Este ensaio introduz os modelos baseados no DEM e as aplicações na JFE Steel. Dois modelos matemáticos baseados no DEM têm sido desenvolvidos para calcular o fluxo sólido e o campo de esforço no alto-forno. Embora os modelos não levem em consideração a força de arrasto do líquido e do gás, os resultados concordam com aqueles do experimento do modelo de escala e análise de dissecação. O cálculo DEM revelou o seguinte: Um leito compacto num alto-forno é apoiado pela formação de uma estrutura em rede por partículas que recebem um esforço pesado. E o esforço no ponto de contato do coque na rede pode exceder a resistência compressiva. O ângulo do eixo afeta grandemente o fluxo sólido e o esforço num alto-forno.

Palavras-chave: Alto-forno; Fluxo sólido; Métodos dos elementos discretos; Coque.

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1 INTRODUCTION

Due to heightened requirements for reduction of CO_2 gas emissions in recent year, improved productivity and energy efficiency in the steel works has become a social responsibility. Extremely high requirements for CO_2 reduction have been placed on the ironmaking process, which consumes large amounts of coal in reduction/melting of iron ore, and also supplies energy for use in the steel works in the form of combustible byproduct gases. In ironmaking by the blast furnace process, sinter and coke (respectively, agglomerated iron ore and coal) are charged from the top of the furnace, while hot blast is blown into the furnace bottom. As a result, high energy efficiency and productivity are achieved by a countercurrent moving bed reaction. There has been an orientation toward reduced reducing agent rate (RAR) operation and increased hot metal production by construction of large-scale blast furnaces with inner volumes exceeding $5500m^3$, as well as technical developments including high pressure operation, oxygen-enriched hot blast blowing techniques, blowing of reducing agents through the tuyeres, etc. However, in order to achieve further improvement, a quantitative grasp of the limit phenomena in blast furnace operation and the development of technology for avoiding those limitations are indispensable.

The blast furnace is the largest production process using a high pressure reaction vessel. Because sensing technologies for use in the furnace, which is a high temperature, high load, high pressure environment, are inadequate, and the properties of raw materials are unstable in comparison with other production processes, mathematical models play a key role in understanding the limit phenomena in the blast furnace. Where prediction of operational limits by mathematical models is concerned, based on the results of work by the "Committee on Transport Phenomena in Gas-Solid-Liquid Packed Beds" of the Iron and Steel Institute of Japan (ISIJ), accuracy in predictions of the limits for occurrence of anomalous phenomena has been greatly improved by use of a flooding index, fluidization index, etc.(1) However, because these techniques treat a continuous mesh structure, it was difficult to reproduce the anomalous phenomena as such, as these are discontinuous phenomena. Focusing on anomalous phenomena such as hanging, slip, channeling, deteriorated casting, and the like in the blast furnace shaft, deadman, and hearth, the subsequent ISIJ "Committee on Control of Physical Limitation on Blast Furnace Operation for Minimizing CO2 Gas Emission" elucidated the mechanism of occurrence of these phenomena and their controlling factors, and developed techniques for relaxing and controlling their dynamic limit points.(2) In this process, a discrete calculation technique was used in reproducing the limit phenomena, and some results were achieved.

In elucidation of the mechanism of limit phenomena and quantitative assessment of the limits for their occurrence, study using both continuous models and discrete models, or a combination of the two, would appear to be necessary. However, in comparison with continuous models, application of discrete type models to the blast furnace field is new, and the object of calculations is not the blast furnace as a whole. At present, the discrete model approach is still at the stage of partial modeling, focusing on only some phenomena. This report describes examples of application to the blast furnace to date, mainly at JFE Steel Corporation, and discusses issues for application of the discrete element method.

2 MATERIALS AND METHODS

The discrete element method (DEM) was introduced in the field of civil engineering by Cundall et al. in the 1970s. Because DEM faithfully reproduces the characteristics of powder behavior, it has now become a representative powder simulation method, including mixed phase flows.(3) In the steel industry, because the raw materials used in ironmaking are powders, DEM was applied to gravitational discharge from the hopper, blast furnace deadman formation, furnace top burden segregation, the behavior of materials in the raceway, etc. by Tanaka et al. in the 1980s.(4-8) Beginning in the 1990s, the applications of DEM expanded to the ironmaking process as a whole, including application to the sintering process by Kano et al.(9) and the coke pushing process by Ariyama et al.

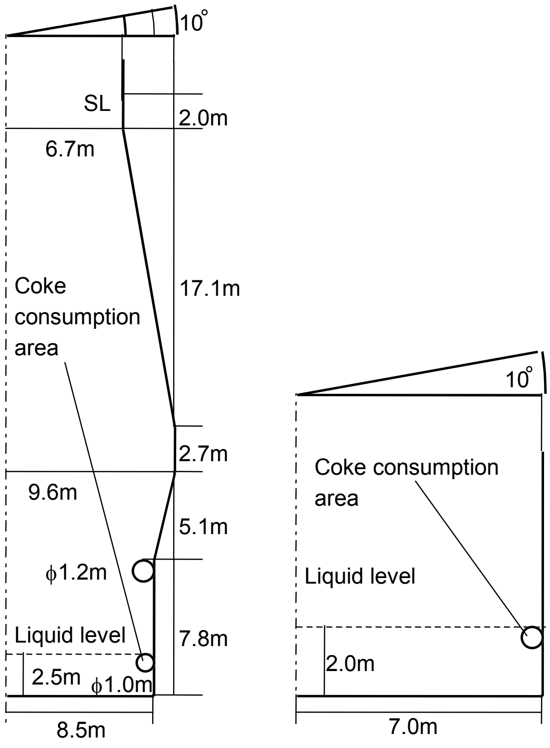
The raw materials used the blast furnace, namely coke and sintered ore, are powders and thus can be analyzed by DEM, except in the cohesive zone and hearth. Since the above-mentioned work by Tanaka et al., DEM simulation techniques have been developed for furnace top raw material charging,(10) segregation at the burden surface,(11) burden descent and deadman formation,(12,13) coke free space formation,(14) and rotation/extinction of particles in the raceway.(15,16) These phenomena can also be reproduced by continuous simulation. However, as a distinctive feature of DEM, it is possible to calculate the particle free surface shape, stagnant region shape, particle segregation, and stress network structure. For example, in estimating the layer profile, it is necessary to adjust the surface function and arbitrary constants based on model experiments. For the shape of the deadman, assumption of the deadman shape itself or tuning of variables is necessary. Where segregation phenomena are concerned, the segregation coefficient must be adjusted by model experiments or investigation of the actual blast furnace. A continuum model is adequate for practical applications, for example, in reproducing actual furnace phenomena in steady-state operation and in operation design. However, in addition to introducing the physical properties of a continuum into calculations regarding particle behavior, which by nature cannot be explained by fluid dynamics, the results will inevitably be an approximation of the motion of particles. Furthermore, because the stress network structure supporting the packed structure of particles is a discontinuous phenomenon, it can be presumed that reproduction by a continuous simulation will be extremely difficult.

Because DEM has features not found in continuous simulations, as outlined above, its range of application in blast furnace analysis is continuing to expand, notwithstanding the fact that DEM is limited to partial models of the blast furnace. The following chapters will introduce examples of DEM analysis of phenomena in the blast furnace by at JFE Steel.

To shorten computation time, two simulations (whole furnace, hearth) were used selectively. The geometry and simulation conditions are shown in Figure 1 and Table 1, respectively. The effects of fluids (gas and liquid flows) were ignored in both simulations. The hearth model assumed that coke is consumed in the peripheral area directly below the tuyeres by direct reduction by the FeO in the slag and carbon dissolution,(17,18) and as a result, the particle size of the coke in the molten pig gradually decreases. The load distribution on the hearth was reproduced by piling particles, as shown in Figure 2.

Table 1. Simulation conditions.

Parameter	Whole BF	Hearth
Diameter d_p	0.2m	0.1m*
Particle density ρ_S	1000 kg/m^3	1000 kg/m^3
Liquid density ρ_L	6700 kg/m^3	6700 kg/m^3
Particle number N	30000	30000
Poisson's ratio ν	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	$k_n/[2(1+\nu)]$	$k_n/[2(1+\nu)]$
Time step Δt	10^{-4} s	10^{-4} s
Discharging rate at raceway	500 /s	
Discharging rate at hearth	0, 33, 50, 143/s	1300 /sec**



(a) (b)

Figure 1. Geometries used in DEM simulation of blast furnace solid flow: (a) whole BF model and (b) hearth model.

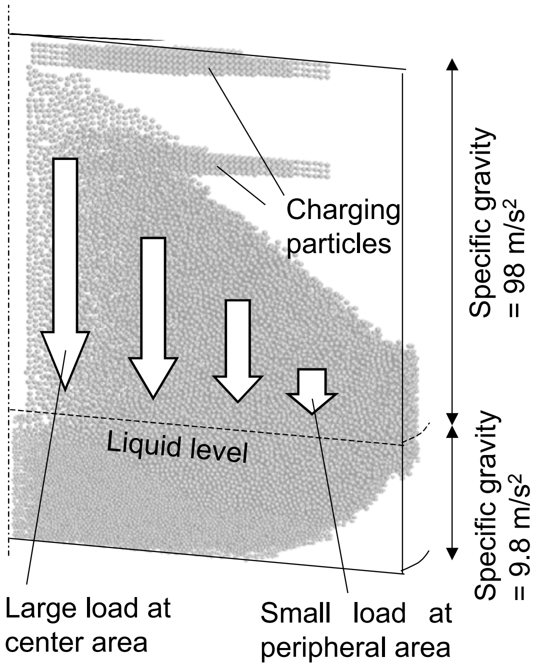
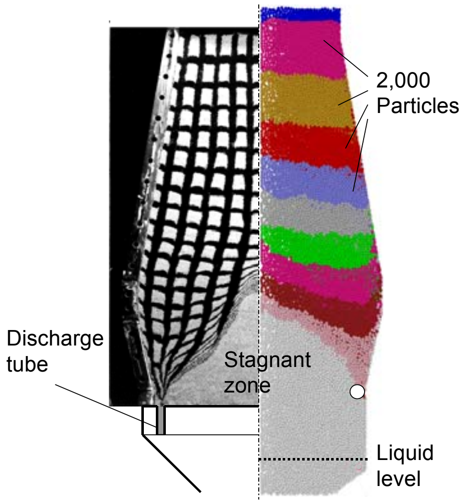


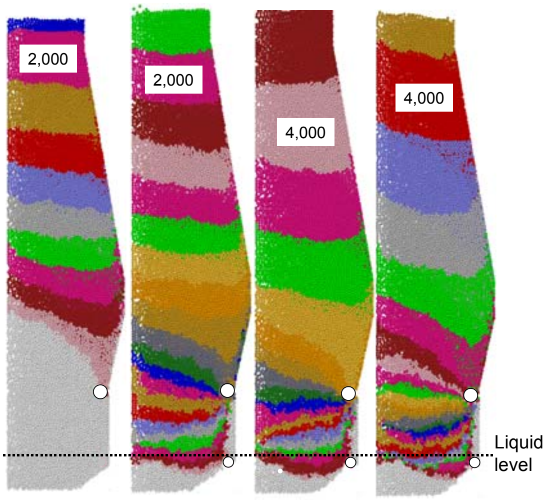
Figure 2. Reproduce burden load distribution by particle piling and large gravity.

Validation is indispensable in numerical simulations, including DEM. The simulation results when particles are discharged from the raceway position under a condition of no gas flows are shown in Figure 3, in comparison with the results of a scale-model burden descent experiment.(19) It can be understood that the calculated deadman volume (stagnant zone) and timeline profile show the same tendencies as in the model experiment. The results of a simulation of the effect of hearth coke consumption on renewal of the stagnant zone are shown in Figure 4. It can be understood that the stagnant zone cannot be renewed without coke consumption (Figure 4a). The calculated results show that the intervals between the timelines in the hearth are narrow in the peripheral zone and center zone, and wide in the intermediate area (Figure 4b-4d). The results of a dissection analysis of No. 4BF at Mizushima Works (now West Japan Works (Kurashiki District)) and calculated solid flows in the hearth are shown in Figure 5. It can be understood that the features of the timelines by DEM simulation are similar to the crystallite size distribution (distribution of hearth coke graphitization; Figure 5a) 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, the results confirmed that a coke powder zone like that observed in the dissected furnace forms in the stagnant zone (Figures 5b, 5c).



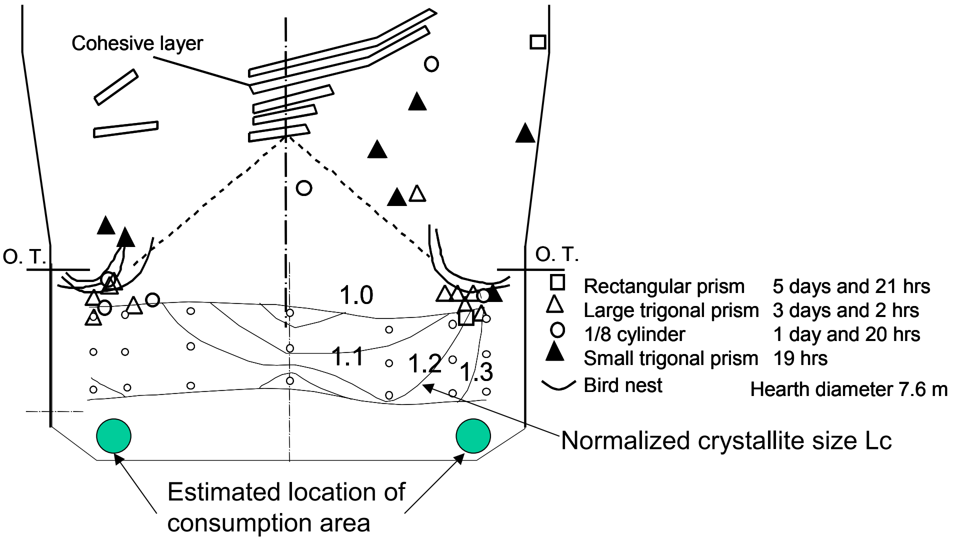
(a) (b)

Figure 3. Burden descending timeline and stagnant zone shape: (a) 1/30 scale model experiment and (b) simulation.



(a) (b) (c) (d)

Figure 4. Effect of hearth coke consumption on stagnant zone renewal: (a) 0/s; (b) 143/s; (c) 50/s and (d) 33/s. Particle colors are changed every certain number shown in the figure.



(a)

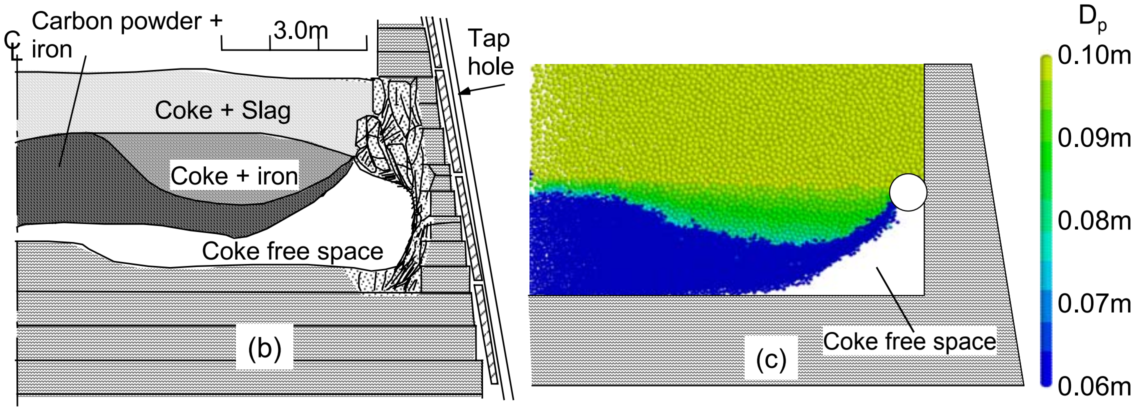


Figure 5. Dissection analysis Results of Mizushima No.4 BF: (a) crystallite size distribution; (b) packed bed structure and coke free space shape and (c) calculated particle diameter distribution.

3 RESULTS AND DISCUSSION

Design of the body of the blast furnace is extremely important from the viewpoints of stability of burden descent, and in turn, stability of blast furnace operation and furnace life. A factor which is considered important in stable burden descent is the furnace profile, and in particular, 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, and conversely, descent in the wall area is delayed when the shaft angle is large.(20) In Japan, the shaft angle of blast furnaces is currently in the range of 79°-84°. Based on operating results, this appears to be an appropriate range. Therefore, the effect of shaft angle on burden descent was calculated by this DEM simulation method, with the results shown in Figure 6. With a shaft angle of 75°, descent in the wall area is clearly faster than in the center. On the other hand, with an angle of 85°, delayed burden descent occurs in the vicinity of the furnace wall. This is substantially in agreement with the results of the previous experimental research. The height of the deadman shows a tendency to decrease as the shaft angle increases. This is a result of the decreased angle of the slip line which forms the deadman due to the effect of increased loading of the deadman when the charging rate and load are increased by expanding the diameter of the furnace mouth and shaft. It can be thought that this fact shows the necessity of higher strength burden materials in blast furnaces with large shaft angles. Based on the simulation results presented above, it is estimated that the current shaft angles of around 80° are appropriate from the viewpoint of stable descent of the burden and prevention of powdering of the burden materials.

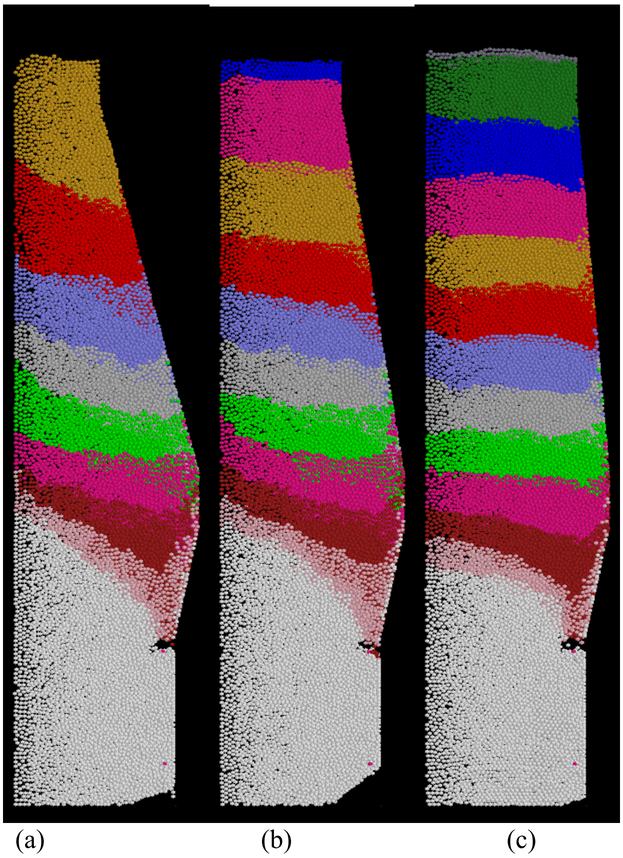

(a) (b) (c)

Figure 6. Calculated effect of shaft angle on solid flow by DEM; shaft angles are (a) 75º, (b) 80º and (c) 85º.

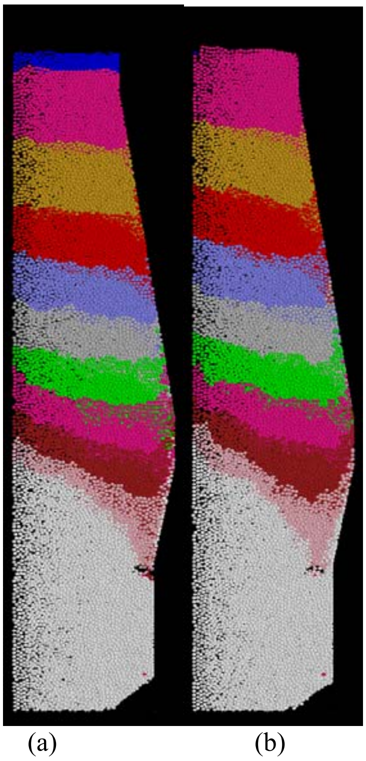

(a) (b)

Figure 7. Calculated effect of tuyere length on dead man size by DEM; tuyere length are (a) 0m, (b) 0.35 m.

Because renewal of the stagnant zone in the blast furnace is slow and its permeability is low, a small deadman cross-sectional area at the tuyere level is considered desirable. Because the cross-sectional area ratio of the deadman increases when the hearth diameter is enlarged in order to increase the furnace inner volume, reduction of the deadman section area by increasing the depth of the raceway becomes a design issue when enlarging the inner volume of a blast furnace. Two approaches to increasing the raceway depth are conceivable, namely, increasing the gas velocity in front of the tuyeres and moving the tuyere tip position closer to the furnace center. It is difficult to calculate the effect of these changes on the shape of the deadman by techniques which approximate a solid flow as a continuum. Therefore, the effect of moving the raceway position toward the furnace center was calculated by DEM, as shown in Figure 7. The results showed that moving the calculated position of the end of the raceway from 1.2m to 1.5m toward the furnace center reduces the volume of the deadman by 18%. This changes also causes the formation of a coke holdup zone at the bosh surface, which means that a reduction in heat load can be expected. Based on these results, within the range where melting and buckling are not problems, a deeper tuyere tip position in the furnace is desirable from the viewpoints of permeability and reduction of heat load.

The packed structure (free space shape, coke particle size distribution) in the blast furnace hearth is important from the viewpoints of stable casting and prevention of hearth wear. Although it is difficult to approximate a solid flow in a buoyant condition using a continuous model, it has become possible to calculate the free space shape and coke particle size distribution by applying DEM. Where hearth coke free space is concerned, it can be understood from Figure 4 that free space forms in the corner parts of the hearth, even under a condition of no gas flows. This indicates that it is difficult to eliminate free space by loading alone when the hearth depth is larger than a certain depth. For a more detailed study, calculations were made using the hearth model. The results are shown in Figure 8. Even when the hearth is shallow, the deadman and free space are not lifted, but are simply cut off by the hearth plate height (Figure 8a, 8b). Moreover, the free space is not extinguished when the burden load is increased by 1.5 times because the stress network extending from the side walls and hearth supports the packed bed (Figure 8c). When the position of coke consumption is an intermediate area in the furnace, the free space becomes largest directly under this area. Because similar results have also been observed in water model experiments using wooden balls.(14) The shape of the coke free space is considered to depend on the distribution of coke consumption, which is governed by the burdendistribution. Figure 9 shows the results of a calculation of particle size distribution in the steady condition. Due of reduction of coke particle size over time, coke with a long residence time forms a coke powder zone of the same shape as that found in the dissected blast furnace (Figures 5, 9a). On the other hand, with a shallow hearth, movement of the hearth coke is virtually impossible, and as a result, coke renewal is concentrated in the peripheral area (Figure 9b). This is considered to indicate a possibility of accelerated erosion of the hearth wall refractory in shallow hearth furnaces due to concentration of the hot metal flow (circumferential flow) in a relatively confined free space. The fact that a large burden load will cause sinking of the deadman and formation of a thicker coke powder zone (Figure 9c) indicates that erosion is more easily avoided under a large burden load condition like that in high O/C, low pressure loss operation, as shown by the Deadman Sinking Index.(21) When the coke consumption position is at an intermediate position, the peripheral region is occupied by fine coke (Figure 9d). This suggests the possibility that casting conditions will deteriorate if Lo/Lc in the intermediate region becomes extremely large and molten droplets concentrate in the intermediate region, as has been observed in an actual furnace using a tuyere probe.(22) Based on the simulation results presented above, a method of forming a stable coke powder zone with the aim of protecting the hearth is shown in Figure 10. If the deadman is in contact with the hearth bottom plate, the conical region in the axial center of the furnace will be pressed by the strong load, and as a result, movement will be impossible and renewal will also be difficult. Other parts will be gradually renewed by supply of coke from above and consumption of coke at the periphery. Extending the renewal time of this moving bed is effective for stable formation of a coke powder zone. As methods of achieving this, increasing the volume of the moving bed and reducing the coke consumption rate at the peripheral area are conceivable. The volume of the moving bed can be increased by sinking the deadman, which is accomplished by high O/C operation or burden permeability improvement, or by reducing the volume of the conical fixed bed by designing a deeper hearth. Peripheral coke consumption can be suppressed by reducing production or by shielding the tuyeres directly above the wear position.

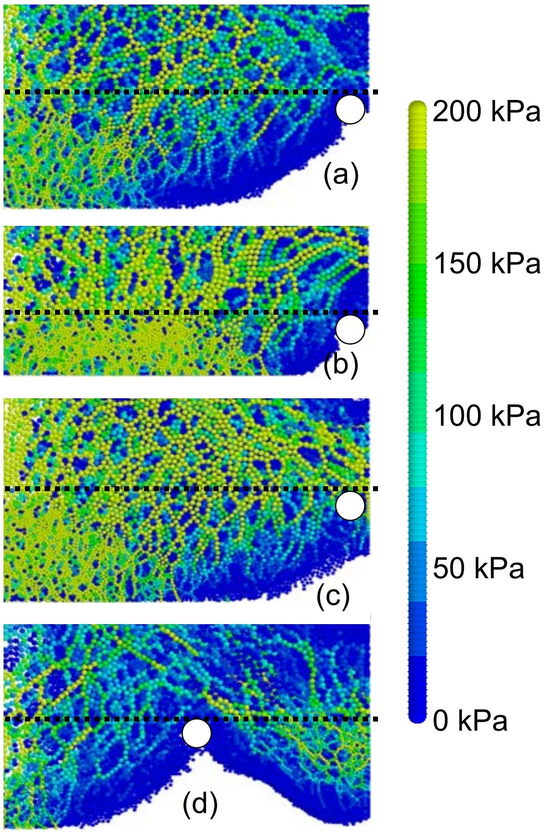


Figure 8. Calculated result of stress field and coke free space shape in hearth: (a) base condition; (b) shallow (1m) hearth; (c) 1.5 times large load and (d) moved consumption area.

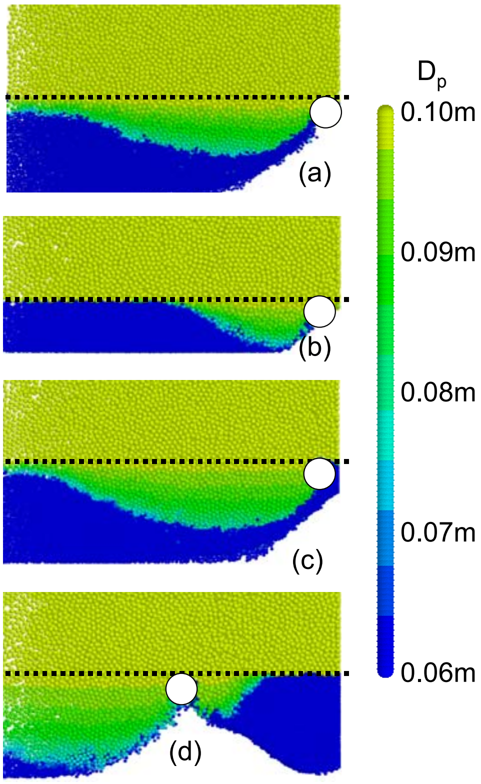


Figure 9. Calculated result of coke diameter distribution in hearth: (a) base condition; (b) shallow (1m) hearth; (c) 1.5 times large load and (d) moved consumption area.

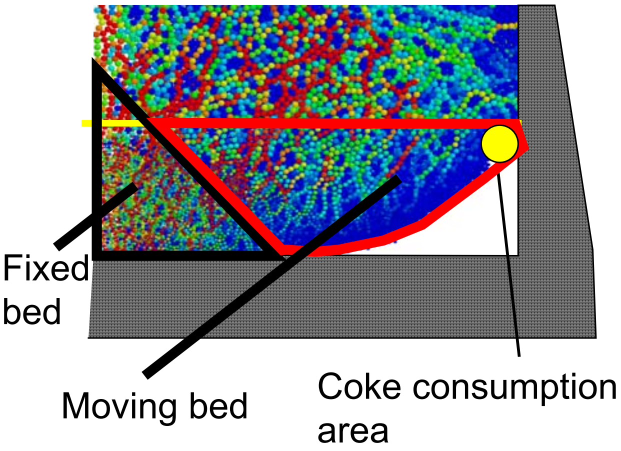


Figure 10. Control methods to form thick low permeability zone

4 CONCLUSIONS

Examples of DEM analysis of phenomena in the blast furnace were presented. Based on the descent of the burden in the blast furnace, stress field, shape of the coke free space in the hearth, and the coke particle size distribution in the hearth, it was possible to propose a evaluate equipment design, including the shaft angle, tuyere design, hearth depth, etc. With future improvements in computer performance and improvements in the DEM technique, faster and more accurate simulations would appear to be possible.

DEM computations involving a practical number of particles only became possible from the 1990s, when rapid advances were achieved in computer performance. Therefore, problems remain in quantitative reproduction of actual phenomena. Even excluding the general problems and limitations of DEM, there are still problems which are difficult to reproduce by DEM, either for technical reasons or due to the computational load. These include the wide range of the particle size distribution and velocity distribution, softening/cohesion phenomena, droplet-related phenomena, segregation, mixing, destruction, and powdering of irregularly shaped particles, multiple types of particles, consumption in chemical reactions, and the like. For example, the time step in DEM is normally set so as to enable calculation of the minimum and maximum velocity particles, and the number of particles in computations increases by the cube of the ratio of the maximum and minimum particle diameters. This means that direct, simultaneous simulation of the behavior of particles in the raceway and burden descent phenomena is unrealistic. As mentioned in the introduction, these points suggest that the development of a technique which integrates partial models of the blast furnace by way of a continuous model is an important challenge for further application of DEM to the blast furnace.

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