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Review

Recent Progress and Future Perspective on Mathematical Modeling of Blast Furnace

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Currently low reducing agent operation of blast furnace has been actively pursued in ironmaking due to the global warming. The precise and reliable control of blast furnace aiming at the low reducing operation is required to attain smoothly the stable operation. It is considered that the mathematical model on the ironmaking process can play an important role to ensure the stable blast furnace operation. A mathematical model is a powerful tool to improve conventional processes and to design new processes in ironmaking. These tendencies and requirements are common to every country. Thus, the development of advanced mathematical models of blast furnace like DEM (Discrete Element Method) has attracted a special attention in ironmaking field. Moreover, the combined model of DEM with the continuum model is under development for the purpose of the accurate understanding of inner state of blast furnace. In this paper, the recent activity and progress on the development of advanced mathematical model of blast furnace and future perspective for desirable model are described.

KEY WORDS: ironmaking; blast furnace; mathematical model; discrete element method; solid flow; particle method; contiuum model.

1. Introduction

Recently, due to the global warming problem, the situation of ironmaking process has shown a remarkable change. Japanese steel industry had placed the focus on the utilization of low grade resources to decrease the steel production cost for a long time. Currently the operating condition of blast furnace is changing to low reducing agent operation. At the same time, the inner volume of the blast furnace has been frequently enlarged over 5 000 m^3 at the relining of blast furnace in Japan to secure the increase in crude steel production rate. The precise and reliable control of large blast furnace based on the low reducing operation is required to attain smoothly stable operation.

From these backgrounds, it is considered that the mathematical model on the ironmaking process can play an important role to ensure the stable blast furnace operation. These basic tendencies and requirements are common to every country. Thus, the development of advanced mathematical models of blast furnace like DEM (Discrete Element Method) has attracted a special attention in ironmaking field. Moreover, the combined model of DEM with the continuum model is under development for the purpose of the accurate understanding of inner state of blast furnace. Various phenomena can be estimated by these kinds of models. In this paper, the recent activity and progress on the development of advanced mathematical model of blast furnace and future perspective for desirable model will be described.

2. Change of Blast Furnace Operation and Mathematical Model

In Japan, the enlargement of blast furnace inner volume have been aggressively promoted to secure the productivity at the relining. The number of large blast furnaces with the inner volume over 5 000 m^3 became over 10 at present. Besides this tendency, low reducing agent operation of blast furnace is an urgent subject, because global warming is considered as a serious issue in Japanese steel industry. Actually, as shown in **Fig. 1**, although the utilization of low grade burden had been promoted until 2000, blast furnace operation is currently going towards low reducing agent. The low reducing agent operation with large blast furnace

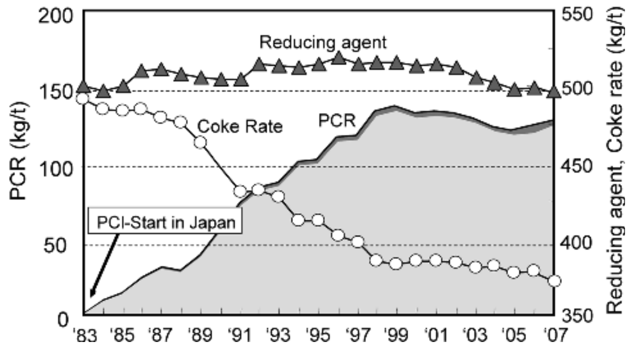

Fig. 1. Transition of blast furnace operating condition in Japan.

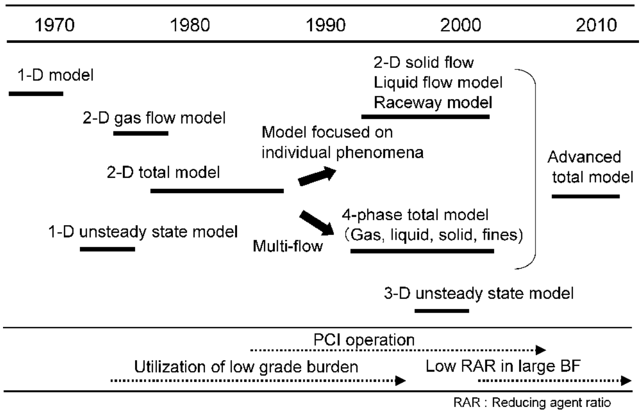

Fig. 2. Progress of mathematical model of blast furnace and operating condition of blast furnace in Japan.

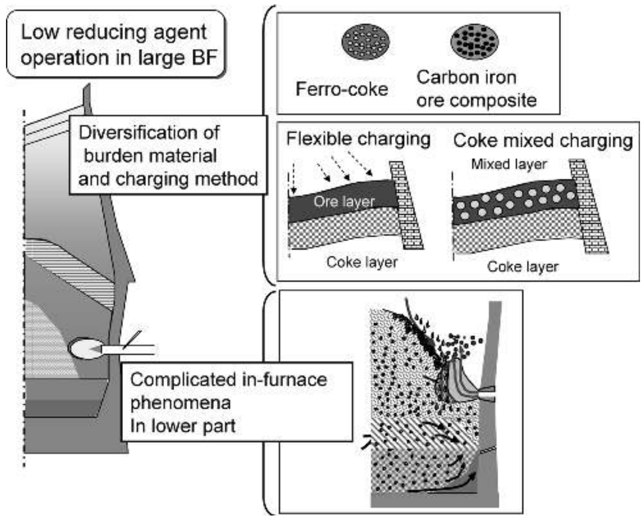

Fig. 3. Change of operating condition and in-furnace phenomena.

occasionally causes unstable gas flow and burden descending due to the enlargement in radial direction and low coke rate.[1] Accordingly, the discontinuance phenomena such as unstable slip of burden and fluctuation of the blast pressure tend to be noticeable in these conditions. In order to attain stable blast furnace operation, precise understanding of in-furnace phenomena is important. Mathematical model of blast furnace can play an important role.

The mathematical models for the blast furnace operation based on the equations of mass, momentum and heat balances and reaction kinetics have been successfully developed. The history of the mathematical model is shown in **Fig. 2**. At the time of 1960th, Muchi *et al.* proposed a comprehensive mathematical model of blast furnace which consisted of a set of ordinary differential equations expressing internal situations of energy, mass and flow of gas, solid and liquid phases together with overall heat and mass balances.[2] These model were enlarged to two-dimensional and three-dimensional models step by step with the progress of computer ability.[3–5] Then, in parallel to the operation change to intensive pulverized coal injection since 1983, element-model for liquid flow in the hearth and combustion behavior in raceway had been actively developed.[6,7] Moreover, the multi flow model for gas, liquid, solid and fines which was called "four-fluid model" had been developed so as to understand the inner state of blast furnace.[8] These continuum-based model was able to estimate precisely the behaviors of gas, liquid, solid and fine coke particle flows and distribution of temperature and reaction degree.

From the above reason such as the low reducing agent operation in a large blast furnace, in-furnace phenomena especially in lower part has become complicated, and charging method and materials are diversified. These changes in blast furnace are shown in **Fig. 3**. Recently, various burden materials such as carbon iron ore composite and ferro-coke have been developed to improve the reactivity.[9.10] At the same time, the in-furnace phenomena in the lower part indicate complicated state. The understanding of the discontinuance phenomena and the microstructure of a packed bed is regarded as important to attain smooth operation of blast furnace. However, these phenomena can not be well simulated with the previous models. In recent years, discrete element method (DEM) is applied to simulate the solid flow in blast furnace.[11,12] DEM can accurately offer the descending behavior for each particle of burden in the blast furnace. Precise distribution of vacancy and force for each particle can be drawn from the result of calculation. With DEM, the charging behavior at the throat and descending behavior of the burden can be precisely estimated. By the combination of DEM with the continuum model, the accurate gas flow which reflects the actual burden descending can be feasible. The complicated in-furnace phenomena will be clarified by those advanced models.

3. Characteristics of Continuum Model and DEM

Firstly, the comparison of DEM and the continuum model are schematically represented in **Fig. 4**. As shown in Fig. 4, in the continuum model, the fundamental equation is applied for every area divided from the object volume, and the distribution of the objects such as gas flow or temperature distribution are calculated. The solid motion is generally derived from the quasi-fluid equation based on the expansion of kinetic theory. On the other hand, in DEM, Newton's 2nd low is applied for each particle.[13] Since the motion of the particle is not averaged in DEM, discontinuous phenomena can be precisely represented, however the object of DEM is limited to the condensed phase. Plenty of contacts between particles are judged in DEM, then the movement of each particle is decided, thus the computational load of the discrete model is extremely large compared with the continuum model. Long time was required from the proposal by Cundall to the progress of DEM on the packed bed in the blast furnace for the restriction of the ability of the computer. Two-dimensional particle method has already been used to analyze the burden distribution at the charging of blast furnace in the 1980's.[11] Since then, DEM had been applied for modeling of burden charge at the throat, solid flow, solid motion near the raceway, renewal of deadman, and motion of coke in the hearth. However, computation load for calculating all particles in the blast furnace is too large. That is the subeject of DEM for applying the blast furnace. In DEM calculation, since the discrete time should be enough short, the iteration steps will be huge number for long term simulation. Moreover,

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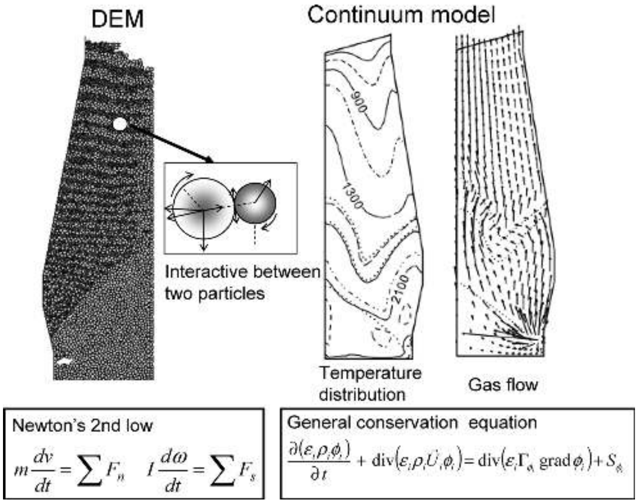

Fig. 4. Comparison of DEM and the continuum model.

an appropriate method for optimizing physical properties of particle which are irregular and changeable in the furnace must be established. Although some subjects on the application of DEM to blast furnace still remained, further development of DEM simulation which satisfies current needs of the blast furnace is possible.

4. Recent Progress on Application of DEM to Blast Furnace

4.1. Simulation of Burden Charging

The blast furnace performance mainly depends on controlling burden distribution at charging and the blast condition. Therefore, burden charging method is an important factor for the blast furnace operation. Formerly, experiments with scale models had been carried out for analyzing burden behavior at the charging. Firstly, two dimensional DEM was introduced for simulating motion and distribution of burden on the surface of burden at the beginning of the 80's. DEM provides analysis of segregation in the bunker and hopper, burden flow at the shoot, and movement on the surface at the throat. Those are difficult to analyze by the scale model. Kajiwara *et al.* simulated motion of the burden charged from the bell by two dimensional DEM, and analyzed particle size distribution on surface at the throat. Then, the segregation phenomena was semi-quantitatively discussed.[11] Function of the movable armor[14] and influence of variations of diameter and density of particle[15] were analyzed with the DEM for charging from the bell.

Recently, number of particle which can be dealt with DEM is increasing with development of computer capability. DEM simulation with over 1 M particles has been carried out in three dimensional DEM.[16,17] The particle dealt in DEM is sphere shape, however, shape of actual burden is irregular, therefore influence of shape should be cautiously considered. In order to represent shape of the burden, cluster particle composed of a couple of spheres as shown in **Fig. 5**, was employed.[18] Behaviors of particle on surface of packed bed in the shaft were compared with various particles. Influence of composing such cluster was not significant, and controlling the physical parameters of sphere particle was suitable for the computation of solid motion. Segregation of particle in the flow from the chute of bell-less system[17] and size distribution on surface of the packed bed[19] are analyzed in large scale DEM. As shown in **Fig. 6**, solid flow varies with a variation in the rolling friction which represents a factor of particle shape. Especially, shape factor affects on motion of particle in flow from the chute of bell-less charging system, significantly. Validity of the rolling friction was confirmed in comparing the calculation and experimental results. Moreover, it was proposed that installing rolling friction parameter which has specific range is an effective method for representing irregularity of the actual burden. Three-dimensional simulation for the charging of burden considering the property of particle was reported as shown in **Fig. 7**.[19]

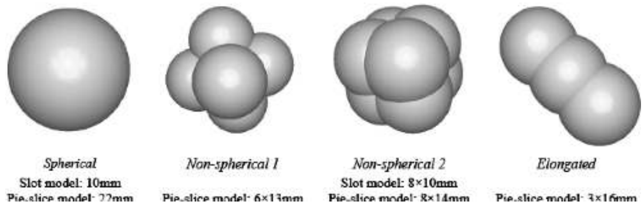

Fig. 5. Tablet shaped particle using multi-sphere element method.[18]

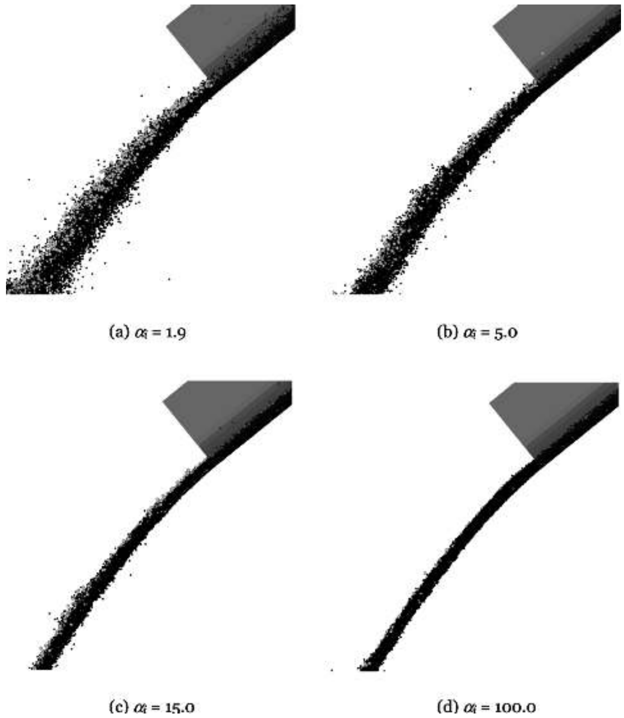

Fig. 6. Influence of rolling friction on discharging behavior.[19]

Since the behavior of particles at the charging can be represented by limited number of moving particle for a short time, the computation load can be restricted within reasonable extent, therefore charging phenomenon of burden for the blast furnace is a suitable subject for DEM simulation. However, optimizing parameters of particle such as rolling and sliding frictions is important for accurate simulation.

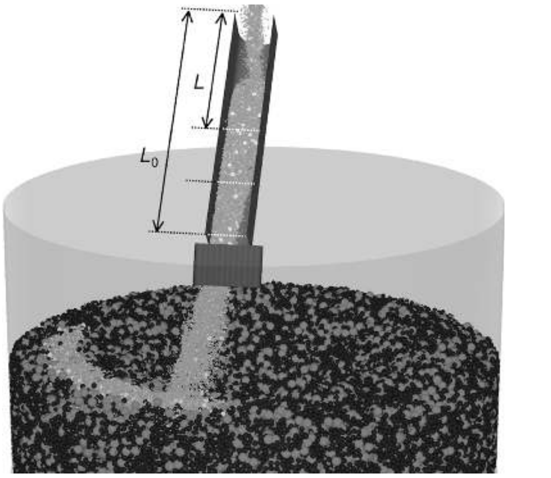

Fig. 7. Particle flowing behavior during charging derived by DEM.[19]

4.2. Solid Motion in Packed Bed of Blast Furnace

4.2.1. Total Analysis of Solid Motion

Burdens charged from charging device are composed of layers of coke and ore in shaft of the blast furnace. Thickness of each layer is about 1 m at the throat. Indirect reduction of iron ore and gasification of coke occur through the gas–solid mass transfer in the layers in the packed bed. Then temperature of burden rapidly increases by heat transfer between gas and solid during burden descending, and then a part of ore melts at the cohesive zone. Direct reduction of ore, melt of oxide impurity, reduction of iron ore and dissolution of impurity into molten iron occur below the cohesive zone. Totally, overall reaction in the blast furnace is related to behavior of solid movement in the shaft and belly, thus many researches had tried to simulate the solid flow in the blast furnace. On the basis of the continuum model, the four fluids model which simulate distribution of temperature, composition, reaction ratio, and solid, liquid, gas and powder flow had been developed.[8] Meanwhile, discontinuous phenomena such as disintegration of coke and ore, renewal of deadman, slip and scaffold can not be represented by the models. Since the discontinuous phenomena affects on stability of gas and solid flow and reaction in the blast furnace, these items should be well controlled. The precise representation of such discontinuous phenomena is desired by using DEM. Actually, DEM has been applied for the solid motion of packed bed in the blast furnace.

Zhou *et al.* have carried out the simulation of solid flow, stress distribution between particles, velocity of particle, stream line and porosity in the blast furnace by two- and three-dimensional DEM in slot model. The experimental result in scale model with bead particles was compared with the result of DEM. Accuracy of the calculation result was discussed.[12] The flow patterns of particles in a scale model and DEM are shown in **Fig. 8**. The irregular flow of stagnant zone around dead man can be observed. Also, Kawai *et al.* simulated variation of sold flow pattern and shape of dead man with center charging of a high density coke. In the scale model experiment, glass particles are charged at center of alumina packed bed. The flow pattern is shown in **Fig. 9**.[20] Center charging of high density particle decreases the height of deadman.

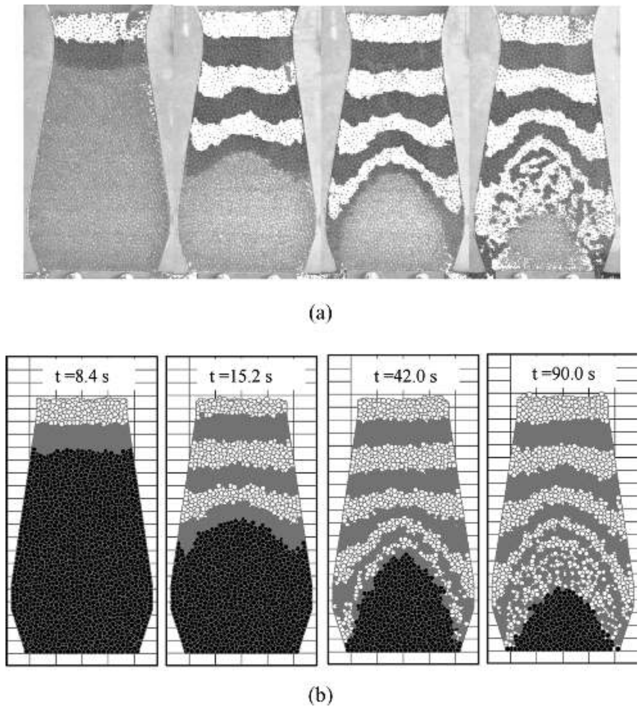

Fig. 8. Solid flow patterns from initial to steady state observed in the physical experiment with 2D slot model (a), and particle simulation (b).[12]

Nouchi *et al.* focused on stress distribution of coke bed in the blast furnace by using characteristics of DEM. A sector shaped three-dimensional blast furnace model based on the actual size and enlarged coke particles was employed for the simulation. Stress distribution between particles are shown in **Fig. 10**.[21] Stress networks of high pressured particles are clearly observed, and the structure does not easily vary with descending of the packed bed. Analyzing distribution of the stress between particles would be an effective method for deciding coke strength required in blast furnace. The energy of impact from contact force between particles in the drum mixer is calculated by DEM. Then the energy was compared with the drum index (DI).[22,23] If the relationships among energy of impact, DI and coke strength in blast furnace become quantitatively clear, these results will be a very important information for determination of the actual strength required for blast furnace. Moreover, the appropriate charging method considering the sufficient coke strength for each position at the throat can be practically determined.

Regarding more realistic burden descending behavior, Mio *et al.* has derived solid motion of packed bed composed with layers of two different kind of particle.[24] In the simulation, 9 m height and 0.575 m depth slot shaped, three-dimensional DEM model of the blast furnace, and 500 000 sphere particles of the actual size were employed. Position of the cohesive zone was arbitrarily given, and iron ore particles shrink below the zone. The calculated descending behavior of particles is shown in **Fig. 11**. Also, the fluctuation of descending velocity was obtained from the calculation.

The burden in blast furnace is influenced by the drag force from gas flow, thus the effect of the gas flow on the

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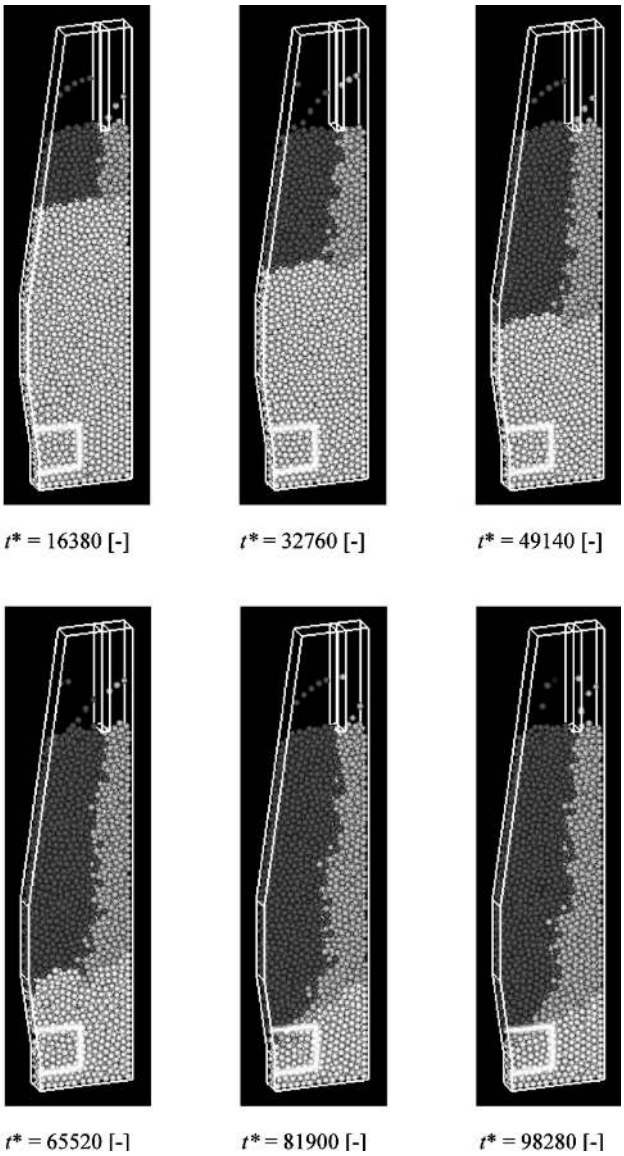

Fig. 9. Simulated solid flow pattern with center charging method.[20]

solid motion have been considered for precise analysis of actual solid flow in blast furnace. Inada *et al.* had installed the drag force into DEM of two-dimensional slot model.[25] The porosity in the packed bed can be derived from result of DEM and affects on the gas flow. The influence of blast gas volume on the solid flow was investigated. According to the results, the height of deadman increases with an increasing in gas volume.

4.2.2. Significance of Physical Parameters of DEM and Solid Motion

In DEM calculation, discrete time will be taken less than about 10^{-5} or 10^{-4} s. The instantaneous solid motion in the hopper, at charging and around raceway can be analyzed in brief duration. Then those can be simulated within the actual time scale. However, the average residence time of burden from the throat to raceway takes about 8–10 h. Accord-

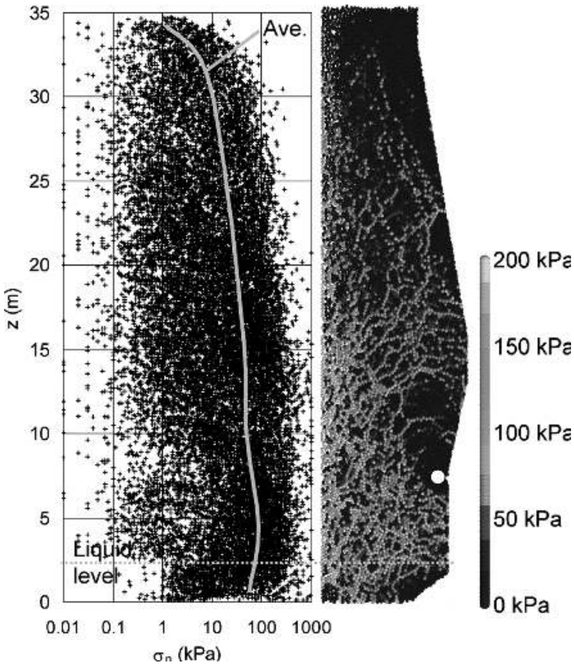

Fig. 10. Calculated normal stress distribution and stress field.[21]

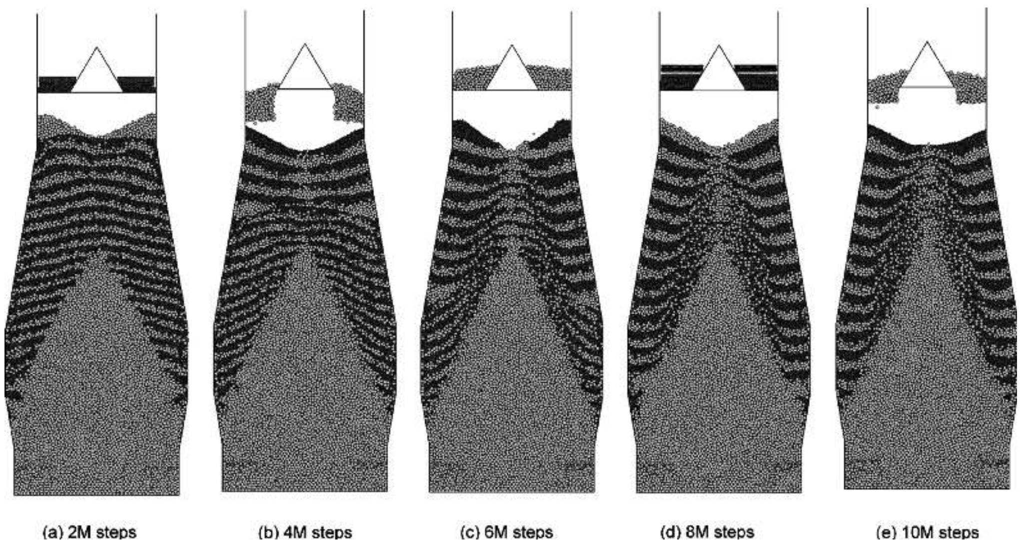

Fig. 11. Snapshots of burden descending behavior in blast furnace.[24]

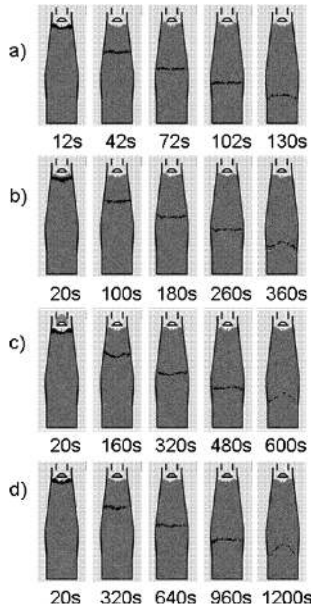

Fig. 12. Change of layer structure of tracer during descending with various descending velocity in DEM (particle diameter: 1.0 cm, α=3.0).[26]

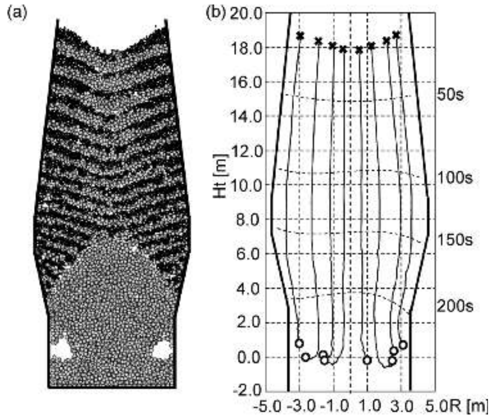

Fig. 13. Descending behavior of burden in blast furnace ((a): shape of layers, (b): line of flow on vertical cross section, Ht: height from tuyere level).[28]

ingly, in order to calculate the burden descending in actual time scale, step of the calculation becomes huge number. Calculation of all particles in the shaft in actual time scale by DEM leads to an unfeasible method. In the previous studies, several methods of using nondimensional time or accelerating the solid motion were employed to mitigate the computation load. Natsui *et al.* had investigated the influence of variation of descending velocity on the behavior of packed bed in blast furnace by comparing the results of descending behaviors with three-dimensional DEM and a semicircle cold model.[26] The descending velocity of solid in a whole blast furnace is controlled by disappearing particles of coke entrained in raceway at arbitrarily-specified interval by DEM. The layer shape change of tracer particles during descending at various velocities are shown in **Fig. 12**. The influence of acceleration on the layer shape is small, however as to the local particle movement such as slip and variation of particle velocity the acceleration of DEM calculation arises the deviation from the actual state. The influence of rolling friction on the descending behavior was also studied. Other researches have been investigating the influence of physical property of particle on the solid flow in blast furnace. Adema *et al.* employed cluster-based particle for representing shape of the actual burden, and showed the influence of shape of particles on flow pattern and height of deadman.[18] Influence of the cluster shape on solid flow at the charging was not clear,[16] however the influence on solid motion in packed bed was observed more than in free flow. Ueda *et al.* studied the influence of harness of particle on flow pattern in the packed bed by three-dimensional DEM with two kind of particles, and obtained that softening of particle up to 1/100 in hardness does not affect on the flow pattern significantly.[27]

On the basis of optimized physical parameters, the overall solid motion in blast furnace was carried out by Natsui *et al.*[27] The calculated burden layers and stream lines by DEM are shown in **Fig. 13**. At the same time, the normal stress distribution in total blast furnace, at the throat and nearby raceway are shown in **Fig. 14**. In Fig. 13, the stress network can be observed, however it shows more complicated state than previous study.[21] It is estimated that these differences are derived from the boundary condition of wall and physical parameter such as hardness of particle. Since the stress network is influenced by particle velocity, the stress network nearby raceway changes with time as shown in Fig. 14.

4.3. Motion of Particle around Raceway

Raceway is formed in front of tuyere by hot blast. The shape and stability of raceway affect on stability of gas and solid flows nearby raceway and deadman. Accumulation of unburnt char derived from pulverized coal and coke fines in the deadman tends to prevent the stable gas flow in the lower part of blast furnace. Accordingly, the analysis on movement of gas, solid, and powder around raceway is so important to secure the stable operation of blast furnace. Many hot and cold scale model experiments had been performed for analysis of gas flow around raceway. Moreover, the multi-fluid continuum models had been developed. Solid particles in the raceway moves rapidly and irregularly, therefore particle method would be suitable for representing the motion of particles in the raceway. The drag force of gas flow moves particles, and the porosity of packed bed affect the gas flow, thus the combined continuum and discrete model (CCDM) has been developed for analyzing the phenomena around raceway. CCDM is composed of particle method such as DEM and continuum model, where the gas flow derived from the porosity of packed bed by DEM and solid motion including drag force of gas flow by continuum model are combined.

Firstly, Xu *et al.* reported the formation and cyclical fluctuation of raceway by the combination of the gas flow by a continuum model and two-dimensional DEM.[29] Also, Nogami *et al.* had analyzed raceway by CCDM composed of FDM and DEM.[30] As shown in **Fig. 15**, the shape of raceway obtained by DEM was compared with experimental results, and the validity of DEM simulation was mentioned as follows. The reaction of coke was represented by shrinking of the particle in DEM. The FDM including combustions of coke and pulverized coal provides distribution

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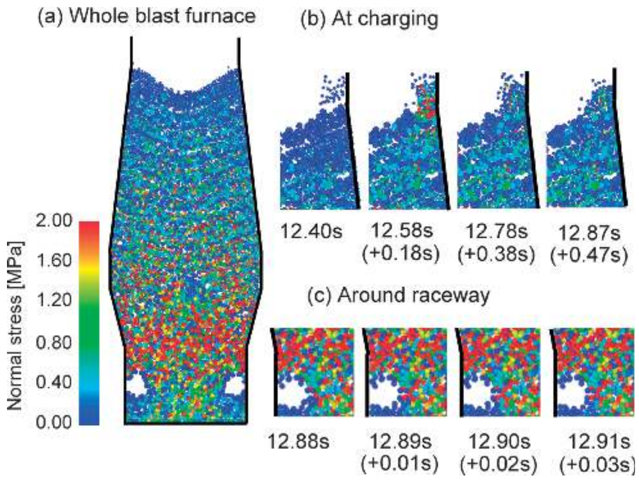

Fig. 14. Normal stress distribution at throat and around raceway.[28)]

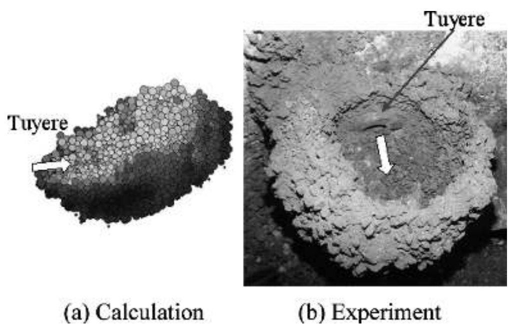

Fig. 15. Raceway shell derived from calculation (a), and experiment (b).[30)]

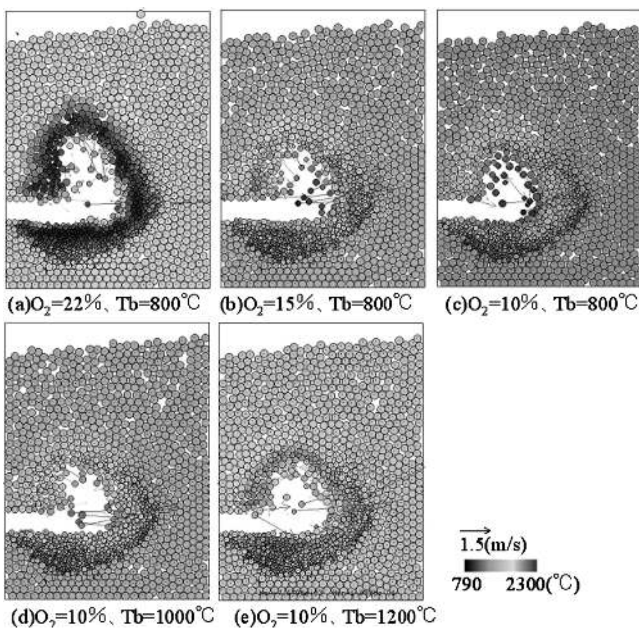

Fig. 16. Calculated raceway shapes (O_2: O_2 concentration of blasting gas. Tb: blast temperature).[30)]

of temperature and composition of gas. The influence of variation of blast condition on the shape of raceway such as oxygen enrichment is clearly represented as shown in **Fig. 16**. The height and depth of raceway increased with an increasing in oxygen enrichment and temperature of blast

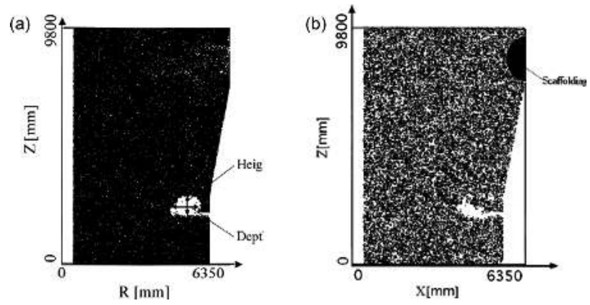

Fig. 17. Calculated instantaneous coke particle location (a) $T=0.8$ s and (b) $T=6.0$ s with a scaffolding.[32)]

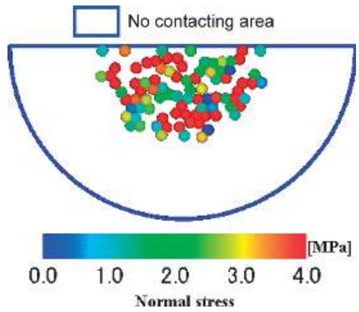

Fig. 20. Calculated normal stress acting between coke and bottom of hearth.[41)]

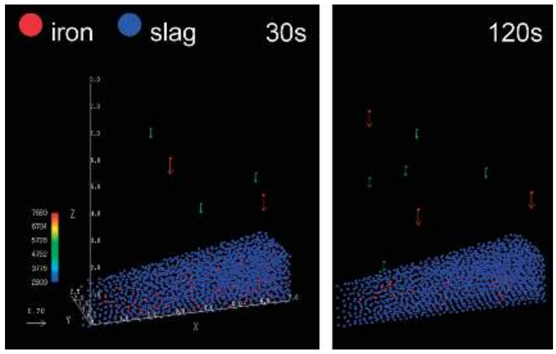

Fig. 21. Dripping and accumulate behavior of iron and slag.[42)]

gas, respectively.[30)]

Umekage and Yuu proposed a hard sphere model for two body interaction of powder particles based on direct simulation of Monte-Carlo Method and finite difference method for the numerical analysis of Navier–Stokes equations with the interactions between gas and particles for the gas flows. Namely, they assembled a three-dimensional CCDM considering interaction of solid and gas phases.[31–33)] The low porosity region which represents gas flow resistance was set at position of cohesive zone. The locations of coke particles near raceway are shown in **Fig. 17**.[33,35)] It is shown that depth and height of the raceway vary with time. Gas flow, coke movement and porosity also vary with the fluctuation of raceway. Influence of scaffolding over the tuyere on solid motion and gas flow near raceway was demonstrated. Influence of angle of tuyere on the gas flow was simulated and it is shown that downward blowing decreases angle and height of deadman. Nakano *et al.* calculated motion of solid and gas around raceway and analyzed stability of raceway by three dimensional DEM in a sector shaped region.[34)]

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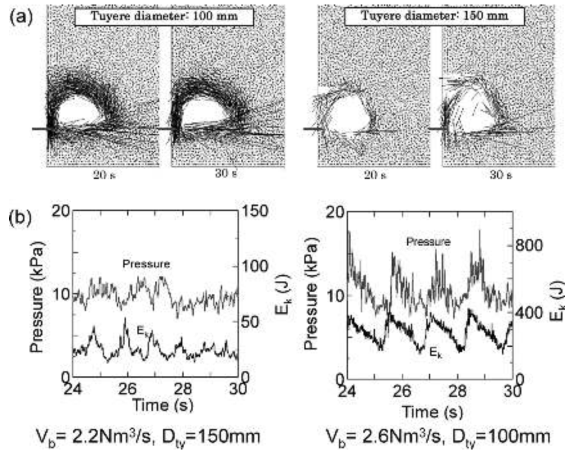

Fig. 18. Effect of blast condition, (a) on raceway stability, and (b) on changes of pressure and kinetic energy.[34]

Shape and pressure of raceway and kinetic energy were derived for various diameter of tuyere and volume of blast gas. Change of pressure and kinetic energy with unstable raceway caused by variation of tuyere diameter and blast gas volume are shown in **Fig. 18**.[34] Both of them show fluctuation with a period of 1 s. Increasing diameter of tuyere is positively correlated with pressure and kinetic energy, and that of amount of blowing gas is negatively correlated with them. Both of higher and lower energy input with blowing causes the instability of raceway. Influence of gas volume on shape of the raceway was studied by two dimensional model which including solid and gas.[35]

Natusi *et al.* discussed the appropriate way to decide contact and rolling frictions of particle and demonstrated influence of the frictions on the solid motion by three-dimensional DEM in sector shaped region near tuyere.[36] The ununiformity of solid motion in cyclic direction at tuyere level was analyzed. The variation of gas flow and pressure caused by changing porosity due to scaffold was analyzed by Kadowaki *et al.*[37]

4.4. Analysis of the Phenomena in the Hearth

The abrasion of refractory is an important factor which decides life time of a blast furnace, therefore controlling of pig iron flow in the hearth is an important issue. The hearth of blast furnace are mainly consisted of coke bed, slag and molten iron. Those react and affect on each other. Recently, behavior of molten pig iron and slag in the hearth are analyzed by continuum models.[38–40] The renewal of deadman and the generation of free space are caused by buoyancy of molten iron, consumption of coke in tuyere and carbonization of coke, and the motion of coke particles in the hearth is located in a complicated state. Thus, the application of particle method for coke motion in the hearth is an effective simulation method. The renewal of deadman was considered to be as an object of DEM simulation. Kawai *et al.* investigated the renewal mechanism of deadman and showed that coke in the deadman moves to raceway from downward. The renewal of deadman caused by the buoyancy was analyzed by three-dimensional DEM in sector shaped region. As shown in **Fig. 19**, distribution and stress of coke are influenced by the position of coke consumption and the level of molten pig iron.[21] The region of the free space

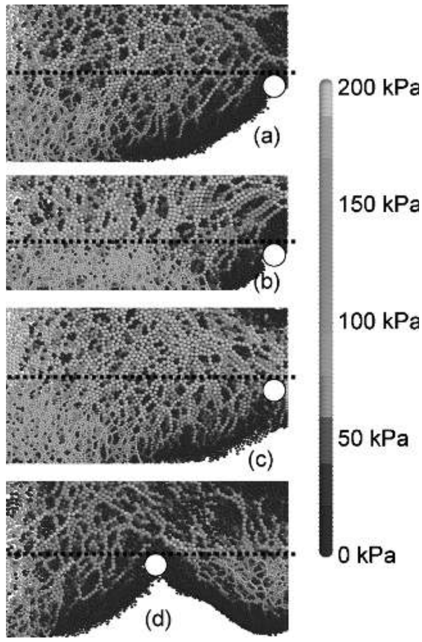

Fig. 19. Stress field and coke free space in hearth: (a) base condition, (b) shallow (1 m) hearth, (c) 1.5 times large load and (d) moved consumption area.[21]

varies with variation of iron level. The stress network near the bottom is also influenced by the buoyancy. Contact area and stress between particle and bottom considering the buoyancy derived by DEM is shown in **Fig. 20**.[41]

Nishioka *et al.* newly proposed MPS method for simulating motion of liquid iron and slag in coke bed below the cohesive zone.[42] **Figure 21** shows snapshots of dropping molten slag and iron particles in lower part of the blast furnace. In the upper part, the porosity of coke bed affects on the velocity of dropping particles. In the lower part, slag particles are entrapped in the slag phase, iron particle pass through the slag phase. This model can be combined with DEM, and the motion of liquid can be calculated by considering melting position, amount of ore particle at the cohesive zone and the structure of coke bed derived by DEM. Since the buoyancy of molten slag and iron interact with the motion of coke in the deadman, DEM is a suitable method of analysis for the hearth. MPS is a potential method for the motion of dropping particle in melting zone. Combination model of continuum, DEM and MPS would provide the total simulator in the hearth of blast furnace.

5. Future Aspect for Advanced Model

With low reducing agent operation by the large blast furnace, the inner state of blast furnace become complicated. Recently, the charging method and burden materials are diversified. The future mathematical that reflects the above actual operation conditions is required. **Figure 22** shows the conception of desired blast furnace model. The complex layer structure of coke and ore at charging should be precisely described, and it is necessary to treat new high reactive burdens such as the ferrous-coke and the carbon iron ore composite. Moreover, a basic in-furnace phenomena like a reaction of the particle, disintegration of coke, *etc.* can be reproduced by adequately treating the movement of

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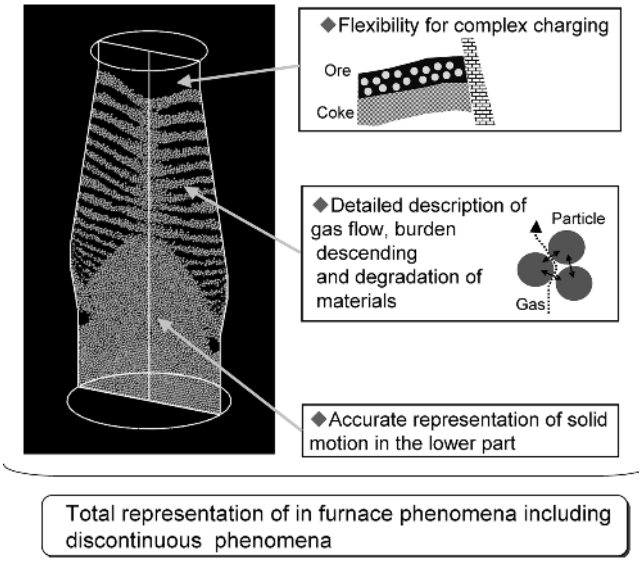

Fig. 22. Desirable mathematical model for blast furnace.

the solid corresponding to the change of the gas flow, the change in diameter of particles and the void ratio. Also, the renewal of deadman, the solid motion in front of the tuyere, the accumulation of the powder, and the generation of the free space corresponding to the enlargement of the hearth diameter are requested.

A hybrid model where the gas, the liquid and the fine particle are analyzed with the continuum model, and a solid and a liquid flow are analyzed with the particle method such as DEM, will provide analysis of the entire discontinuous phenomena in the blast furnace. However, there still remained a lot of subjects to satisfy a highly accurate analysis as the new simulator. The disintegration phenomena of coke and ore and the change of particle size by abrasion and reaction during descending must be so mathematically formulated that they can be installed to model. The conception of new materials such as ferro-coke is much different from the conventional burden, and the new reaction model phenomena must be developed. These information on particles must be quantitatively reflected to the advanced model.

Finally, although the computer capability has been rapidly progressed, the advanced model must be practically useful. The appropriate and practical modeling of various phenomena in blast furnace is successively required to ensure the practicability through the efforts of researchers and engineers.

6. Conclusion

Recently, the situation of ironmaking process has shown a remarkable change. For a long time, Japanese steel industry had placed the focus on the utilization of low grade resources to decrease the steel production cost. Currently low reducing agent operation has been actively pursued. At the same time, the inner volume of the blast furnace has been frequently enlarged over 5 000 m^3 at the relining of blast furnace in Japan to secure the increase in crude steel production rate. From the above reasons, the precise and reliable control of large blast furnace based on the low reducing operation is required to attain smoothly the above target. Then, it is considered that the mathematical model on the ironmaking process can play an important role to ensure the stable blast furnace operation. These tendencies and requirements are common to other countries.

In the past 50 years, mathematical models of ironmaking processes have been developed applying mainly CFD modeling and the models derived has contributed significantly to improve operational efficiency of the processes. From the above backgrounds, the development of advanced mathematical models of blast furnace like DEM has attracted a special attention in ironmaking field to satisfy the above requirements. Moreover, the combined model of DEM with the continuum model is under development for the purpose of the accurate understanding of inner state of blast furnace. In this paper, the recent activity and progress on the development of advanced mathematical model of blast furnace were introduced. Moreover, the perspective for desirable model in future was described.

Finally, it should be emphasized to say consequently that the role of mathematical process models will be more and more important, and be studied much more together with optimization and global evaluation for effective production and substantial decrease in environmental load.

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