（＊掲載記事題目及び掲載頁は変更になる場合があります。）

Reduction of CO_2 emissions from integrated steel works and its subjects for a future study

T.ARIYAMA et al.

Reduction of CO_2 emissions has been discussed using newly developed precise model based on carbon and energy balance in large-scale integrated steel works as a whole. Although there are various means to decrease reducing agent rate (RAR) at blast furnace, preferable way to reduce CO_2 emissions must be chosen considering energy balance in whole steel works. Reduction of RAR at blast furnace together with energy saving at downstream processes is important. Maintaining competitiveness in global steel market must be also considered. Simple reduction of RAR such as improvement of shaft efficiency at blast furnace without energy saving at downstream processes leads to increase in production cost because of increment of purchased energy. Injection of waste plastics and carbon neutral materials such as biomass is better alternative.

Regarding blast furnace operation, under the use of inferior raw materials such as low strength coke as well as high productivity condition, there are many problems to be solved to achieve low RAR operation. It has been reported that drastic change of lower part situation such as increase in coke degradation and accumulation of coke fine causes operation instability at actual blast furnace. Therefore, to attain stable low RAR operation, it is confirmed that new control measures based on fundamental researches to solve various problems should be developed.

(cf. *ISIJ Int.*, **45** (2005), 1371)

Subjects for achievement of blast furnace operation with low reducing agent rate

Y.UJISAWA et al.

The technology which reduces the reducing agent rate by the improvement in the reaction efficiency of blast furnace leads to reduction of hot metal manufacturing cost, but also solution of recent CO_2 emission reduction. The subjects for achievement of the blast furnace operation with low reducing agent rate were described on reduction measures of the carbon consumption and problem of the measures referring to the example of reducing agent rate of the present state blast furnace concerning blast operation and reactive improvement. And, carried out concrete measures were introduced in order to aim at the low reducing agent rate operation.

The following results were obtained.

1) Since it has reached the already high reaction efficiency in present state blast furnace, it is not easy to attempt further reduction of the reducing agent rate.

2) The blast furnace use of high reactivity coke or reduced iron is equal level or over it in comparison with the reduction effect by the assumed blast operation in this paper.

3) The promotion of coke reaction load with the gasification is worried, when it aims at the low reducing agent rate operation by the high reactivity coke use.

4) It is estimated that the threshold also exists for the reducibility of competing ore, when it aims at the low reducing agent rate operation using the high reactivity coke.

5) The use of the low SiO_2 sinter is effective for the improvement on the permeability in the blast furnace, when it aims at the low fuel rate operation. However, the new technology of the permeability improvement is desired, since there is some a limit for low SiO_2 of the sintered ore, when future raw material supply and demand is considered.

(cf. *ISIJ Int.*, **45** (2005), 1379)

Two dimensional cold model study on unstable solid descending motion and control in blast furnace operation with low reducing agents rate

H.TAKAHASHI et al.

Unsteady behavior with bridging/slipping of solid bed in low reducing agents rate operation of blast furnace was simulated using a two dimensional cold model. Alumina sphere was used as representative particle of coke/ore packed bed. Two kinds of deadman particles different in gas permeability was examined. To simulate the effect of cohesive zone on unsteady behavior, a sand layer of lower gas-permeability was charged with a certain thickness at the top of the bed, which descended with a form of cohesive zone when it reached at the lower part. Further, a fine coke layer was set at the shaft bottom with a certain size assuming accumulation of fines. Unsteady phenomenon with the fine coke accumulation was observed with another thin sand layers, charged in the shaft assuming increase of gas-permeability resistance in lower reducing agents rate operation. It was revealed that the ratio of peripheral flow rate to the total gas injection rate had a considerable effect on the discontinuous behavior of both solid descending motion and gas static pressure. The ratio increased with decline in deadman gas-permeability, approach of the simulated cohesive zone to deadman surface and inflow of small particles into raceway. There was a lowest critical position of the simulated cohesive zone for the rapid increase of discontinuity. The bridging/slipping behavior with fines accumulation was significantly affected by the low gas-permeability layers charged in shaft. Setting up the chimney zone of high gas-permeability at the central part was effective to decrease the discontinuous motion.

(cf. *ISIJ Int.*, **45** (2005), 1386)

Development of new simulation method for flow behavior of granular materials in a blast furnace using cellular automaton

N.KATSURA et al.

A new simulation method that permits the large-scale of simulation of coke and granular flow in a blast furnace was developed using cellular automata. The automaton rule consists of the transition rule of constituent particles and interaction rule between particles. The interaction rule is divided into three rules; the collision rule, the static contact rule between particles, and propagation rule of impulsive force through the particle bed. The interaction rule was derived quantitatively on the basis of microscopic information on the interactive force between flowing particles under gravity obtained by DEM simulation. The evolution of granular flow with time can be simulated by defining the equivalent time to one step in automaton simulation, and the state variables in granular flow can be obtained by the proposed simulation method. The validity of the proposed powder cellular automaton method was confirmed by comparison of the simulated flow pattern of discharging flow from a hopper with experimental one. Granular flow of iron ore and coke particles in a blast furnace can be simulated with high speed by the proposed automaton method.

(cf. *ISIJ Int.*, **45** (2005), 1396)

Predicition of stable and unstable flows in raceway using numerical simulation methods for gas and particles

S.YUU et al.

We have numerically simulated the particle and gas flows in the raceway region in an actual blast furnace of which dimension is the same as that of the commercial blast furnace using Distinct Element Method for the computation of the multi-body interaction among coke particles, 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 interaction terms between gas and particles for the gas flows. In the simulations we have taken the existence of softening melting zones into account. The present calculation results indicate the raceway pattern, its fluctuations with various periods. The results also indicate the velocity distributions of coke, powder and gas, and packing ratio distributions of these particles. The dynamical characteristics fluctuate and are unstable. The highly packed coke and powder particle layers are formed in the lower core and in the lower wall regions under the tuyere due to the air and these particle flows.

The high air velocity region appears in the layer between the softening melting zones and the highly packed furnace lower core region, and the unstable high air velocity region is produced near the furnace wall and on the raceway by the existence and the disappearance of softening melting zones. The coke and powder particles and the softening melting zones would yield the unstable state in the furnace.

The powder particles circularly spread and make the circularly multi-layered powder particle clusters caused by the particle collisions and the breakage of clusters. Some of the powder particles flow upward and others are packed in the furnace lower core region by the particle and the air flows.

Our calculated results present an unusual phenomenon example in the blast furnace, that is, the unusual high air velocity wide region touched to the furnace wall is formed due to the effect of the softening melting zones and the accumulation of small coke particles in the furnace center region.

(cf. *ISIJ Int.*, **45** (2005), 1406)

Numerical simulation of blast furnace raceway depth and height, and effect of wall cohesive matter on gas and coke particle flows

T.UMEKAGE et al.

We have presented the calculated results of the

particle and the gas flows in the raceway region in an actual blast furnace of which dimension is the same as that of the commercial blast furnace. We used Distinct Element Method for the computation of the multi-body interaction among coke particles and Finite Difference Method for the numerical analysis of Navier-Stokes equations with the interaction terms between gas and particles for the gas flows.

The calculated results show a typical raceway pattern and typical distributions of gas and particle velocities and void fraction in an actual blast furnace. The results present the size and the shape of raceway. These change as the time and show the unstable and unsteady motion. Both of the depth and the height of raceway periodically change and have roughly two different periods. The calculated mean values of the depth and the height of raceway are fairly in good agreement with the measured data by Matsui *et al.* (*ISIJ Int.*, **45** (2005)). Thus our calculated values present the rough but the proper estimation of raceway characteristics in an actual blast furnace. The unsteady change of the calculated pressure at the nozzle outlet also indicates two different periods of which values agree with those of the raceway. The short period would indicate the usual fluctuation of the raceway and the long period would do the large scale change of the flow. These results show that the raceway grows and shrinks during the short period and greatly changes its shape and size during the long period.

Calculated results present an unusual phenomenon example in the blast furnace, namely the unusual high air velocity wide region touched to the furnace wall is formed due to the air flow penetrated the powder particle wall formed around the outside of the raceway, the effect of the softening melting zones and the size reduction of coke particles in the furnace center region.

We calculated the gas and particle instantaneous velocity vectors, and the instantaneous iso-contour of void fraction with the cohesive matter on the furnace wall in the actual blast furnace. The cohesive matter considerably changes the gas and the particle flows, particularly dose the flows near the furnace wall.

(cf. *ISIJ Int.*, **45** (2005), 1416)

Stress field and solid flow analysis of coke packed bed in BF based on DEM

T.NOUCHI et al.

The stability of blast furnace operation, such as blast pressure, burden descending, liquid holdup and residual amount of slag in hearth, are dominated by the permeability of coke packed bed. The coke degradation in packed bed is caused by abrasion. Then the stress field is calculated by simulation based on discrete element method (DEM) to make clear the abrasion mechanism. Coke free space shape affects on the liquid drainage efficiency and hearth refractory erosion. Then the effects of hearth depth, burden load and coke consumption on the coke free space shape is considered by using the DEM simulation also.

The calculated results show that a force network is formed in the whole of BF and supports the load of burden. The stress of particle in the network is much larger than the average, which can be estimated by continuous simulation. A coke in force network is abraded until the contact cross section larger and contact stress is less than the compressive stress. After then another coke particle participates in force network. Coke abrasion is caused by such force network reconstructions. Coke free space shape is dominated by the solid flow caused by coke consumption in hearth. The coke free space shape, hearth refractory erosion and drainage efficiency can be affected by the hearth depth, burden load and coke consumption in hearth.

(cf. *ISIJ Int.*, **45** (2005), 1426)

Analyses on blast furnace raceway formation by micro wave reflection gunned through tuyere

Y.MATSUI et al.

The blast furnace raceway formation under the intensive coal injection by measurement of micro wave reflection gunned through a tuyere is discussed. As the flow rate of coke as the momentum of coke into raceway decreases by combustion of coal injected into tuyeres, the depth of raceway defined as the maximum position of micro wave reflection is easy to contract. It is expected that this new technology could detect the raceway collapse phenomena in short time and that the stability of raceway in coal injection is different from that in all coke operation. Finally the paper ends by summarizing the effect of raceway formation on unsteady phenomena forcing functional disorder on blast furnace performance of burden distribution for high productivity performance.

(cf. *ISIJ Int.*, **45** (2005), 1432)

Stabilization of tapping hole length by controlling blast furnace raceway depth

Y.MATSUI st al.

On facing the high productivity and elongation of life time in blast furnace iron-making, it is essential to protect the peripheral iron flow formed by a free space in the hearth in addition to maintaining the gas and liquid permeability of deadman. Therefore, it is important to stabilize the length of mud (tapping hole length) which is plugged and formed by hole closing refractory (mud materials), but the phenomena of fluctuation of tapping hole length are not clarified. In this paper, variables affecting the tapping hole length including the raceway depth measured by micro wave reflection struck tuyere are discussed under dimension analysis. As the burden weight above the raceway are balanced to upwind gas, the load to the hearth under the raceway is less than that in the furnace center and a high void ratio area or free space is easy to be formed under the raceway. As the result, it is clarified and quantified that the tapping hole length is recovered from shortage of distance by decreasing raceway depth which promotes deadman to sink further into bottom or increase the void ratio of peripheral area in the hearth.

(cf. *ISIJ Int.*, **45** (2005), 1439)

Analyses on dynamic solid flow in blast furnace lower part by deadman shape and raceway depth measurement

Y.MATSUI et al.

As one of the factors of frequent troubles that occur in the transition period from all-coke operation to PC injection operation in blast furnace as well as increased troubles in recent years, increased size of the blast furnace and high-productivity operation are pointed out. Consequently, great importance is attached to burden distribution control and burden descent condition, or control of melting zone, deadman shape, solid flow at the lower part of furnace and others. In the present study, the reduced stockline surface profile was measured by the reflection intensity of microwave struck from the furnace top after blow-off with stockline reduced, and investigation was made on the countermeasures for changes in the raceway depth and furnace body profile during operation. As a result, it has been clarified that flow-down of coke into the lower part of blast furnace and inflow into the raceway are greatly subject to the existence of deadman which is the packed structure of the lower part of furnace, and further, they are closely related to dynamic behavior of the raceway and affect changes of the furnace body profile.

(cf. *ISIJ Int.*, **45** (2005), 1445)

Development of a visual information technique of nonstationary fluctuations in a blast furnace process

S.MATSUZAKI et al.

By turning stave temperature and shaft pressure data, collected by a number of sensors spatially located circumferentially and vertically in the blast furnace, into images distributed in two dimensions, we have succeeded in quantitatively and objectively visualizing shaft pressure variations and spatial changes caused by slipping in the blast furnace. In addition, combining the two-dimensional distribution of secondarily processed data of changes in space and time with the progress of operation data enables early detection of shaft pressure fluctuations. The conjecture that the uneven distribution of voids in the blast furnace may be the cause of shaft pressure fluctuations has been confirmed by our model experiments. It has been also found that there exists a relationship between the cohesive zone root position, assumed by the visualized two-dimensional image of the stave temperature change over time, and the origins of shaft pressure fluctuations.

(cf. *ISIJ Int.*, **45** (2005), 1452)

Effects of packed structure and liquid properties on liquid flow behavior in lower part of blast furnace

Y.BANDO et al.

Supposing liquid flow in the lower part of the blast furnace, a small trickle bed with abnormal void was used, and the effects of packed structure and liquid properties on the liquid flow behavior were examined. Different-size glass particles coated with PTFE (polytetrafluoroethylene) were packed in the column, and the pressure loss and liquid holdup in the packed bed were measured. The liquid loading and flooding points were obtained from the change in pressure loss.

Both the gas velocities at loading and flooding points decreased with increasing volume fraction of small particle, with increasing liquid viscosity

and with increasing liquid velocity. As the small particle fraction is higher, the total and static liquid holdups increase but the dynamic one decreases. These holdups were expressed by the experimental equations.

The liquid behavior in one void was modeled and analyzed. From the force balance on the liquid droplet at the flooding point the upward and downward forces were examined, and the variation in liquid flow behavior in the lower part of the blast furnace was estimated.

(cf. *ISIJ Int.*, **45** (2005), 1461)

Characteristics of liquid hold-ups in a soaked and unsoaked fixed bed

H.KAWABATA et al.

In most previous works, liquid hold-ups were studied by using a cold model of a fixed bed soaked prior to experiments. However, they did not consider that the dripping zone of a blast furnace is saturated with liquids or with evenly distributed droplets. In the present study, the characteristics of liquid hold-ups and liquid flow were investigated by using a one-dimensional cold model of a fixed bed soaked and unsoaked prior to experiments (initially soaked and unsoaked beds). Packed balls were five kinds, the diameters (D_p) of which ranged from 5.4 to 30 mm. Tap water was used as liquid. Contact angles (θ) for these particle/liquid systems were about 70° and 10° for fluorine-coated particles and non-coated particles, respectively.

Although, under bad wettability condition ($\theta \fallingdotseq 70°$), total and static hold-ups for initially unsoaked bed packed with small balls are remarkably smaller than those for initially soaked bed, the difference in their hold-ups between initially unsoaked and soaked beds decreases with increasing ball size in the bed. In initially soaked bed, total and static hold-ups increase monotonically as ball size decreases, which means the specific surface area increases. On the other hand, in initially unsoaked bed, total and static hold-ups under bad wettability condition indicate maximum values at about $D_p = 10$ mm and decrease abruptly in proportion to a decrease in particle size, despite an increase in the specific surface area. Only restricted liquid droplets and/or liquid rivulets are formed within the packed bed with good wettability condition ($\theta \fallingdotseq 10°$) for initially unsoaked bed, nevertheless liquid is easy to spread out on the solid surface. The influence of the initial bed condition, soaked or unsoaked bed, on liquid hold-ups is great under bad wettability condition.

(cf. *ISIJ Int.*, **45** (2005), 1466)

Influence of channeling factor on liquid hold-ups in an initially unsoaked bed

H.KAWABATA et al.

One of the important factors for minimum energy consumption and CO_2 emission of a blast furnace (BF) is to elucidate the liquid flow phenomena and liquid hold-ups in the dripping zone of BF. Liquid hold-ups were studied by using a cold model of a fixed bed soaked prior to experiments (hereinafter called initially soaked bed), but the existing correlation equations derived from liquid hold-ups under initially soaked bed do not agree with liquid hold-ups under initially unsoaked bed such as the dripping zone of BF.

In the present study, correlation equations for liquid hold-ups in initially unsoaked bed were experimentally derived by a new approach, in which channeling factor (F_c) was proposed and defined as follows: F_c is the ratio of the number of liquid paths per one horizontal line to the number of voids between particles per the same horizontal line, and was measured by using the moving image of liquid paths photographed by a CCD video camera.

By using empirical equation for F_c, hold-ups in initially unsoaked bed were described as the following correlation equations.

Static hold-up

$$H_{S(I\text{-}UB)}(\%) = 0.9 \cdot H_{S(I\text{-}SB)} \cdot F_c^{0.8} \cdot Nc_m^{-1}$$

Dynamic hold-up

$$H_{d(I\text{-}UB)}(\%) = 0.9 \cdot H_{d(I\text{-}SB)} \cdot F_c^{0.5}$$

Total hold-up is the sum of H_S and H_d

$$H_t(\%) = H_S + H_d$$

where, $Nc_m = 1 + (\cos\theta)^3$, and subscripts I-SB and I-UB designate quantities associated with initially soaked and unsoaked beds, respectively.

The comparison with the previous liquid hold-ups shows that the estimated hold-ups are in good agreement with the experimental values for any particle diameters used and both contact angles of 10° and 70° under initially unsoaked bed.

(cf. *ISIJ Int.*, **45** (2005), 1474)

Analysis of reaction rate between solid carbon and molten iron by mathematical models

H.SUN

The factors affecting the carbon dissolution rate into liquid iron and the interdependency between these rate influencing factors were discussed with aid of a kinetic model. These rate influencing factors include temperature, carbon structure, interfacial active elements, metal composition, liquid agitation, wettability between solid and liquid, solid particle size, ash in carbonaceous materials and side reactions.

Experiments were carried out on carbon dissolution from graphite and coke into liquid Fe–C alloy using resistance or induction furnaces at 1 573–1 873 K. The kinetic parameters describing carbon dissolution rate were obtained from the comparison of observed carbon dissolution rates and model calculations. The dissolution rates at higher temperatures or in an induction furnace were found more rapid than those at lower temperatures or in a resistance furnace. The mass transfer in liquid was found to be the major limiting step for the carbon dissolution process.

(cf. *ISIJ Int.*, **45** (2005), 1482)

Numerical analysis on behavior of unburned char and fine coke in blast furnace

H.NOGAMI et al.

A mathematical model of blast furnace operation, which is able to estimate the behaviors of the unburned char and the fine coke simultaneously, has been developed. The model based on the multi-fluid theory treats dynamic powders that are moving entrained by the gas stream as individual phases and static powders as solid components. The former takes conservation equations of momentum, thermal energy, chemical species and continuity. The latter takes only mass balance equations of chemical species, and shares fields of flow and temperature with the other solid components, such as lump coke, sinter, and so on. In the simulations, the unburned char is derived from the pulverized coal injected from the tuyere, and there is no difference in model treatment between the unburned char and the pulverized coal. The fine coke is generated uniformly in the raceway region from the coke particles, and the generation rate is determined by a kinetic treatment. The simulation of the blast furnace operation by this model revealed that the unburned char and the fine coke having different diameters and densities show different flow patterns especially in the cohesive zone and deadman. Consequently these two powders formed different areas of accumulation and reactions while large amount of powders were deposited in the deadman zone regardless of difference in flow patterns.

(cf. *ISIJ Int.*, **45** (2005), 1489)

Effect of various in-furnace conditions on blast furnace hearth drainage

K.Nishoka

Stable blast furnace operation is required to reduce energy consumption and CO_2 emission in iron and steelmaking industry. For the stable blast furnace operation, precise controlled drainage is one of the important factors. Therefore, in this work, the effect of coke diameter, void fraction, coke diameter distribution, coke free space, impermeable zone, slag viscosity in a blast furnace hearth on drainage rates, gas–slag and slag–iron interfaces shapes and maximum gas–slag interfaces height were examined with a three-dimensional mathematical model.

The results indicate that the conditions of the peripheral region at the taphole level determine the residual slag volume. The packed bed in the region 2.0 m from the taphole has about 50% of contribution to the residual slag volume. The void fraction change has the largest effect on the gas–slag interfaces height. The coke diameter distribution has little effect on the total drainage rate as well as the coke diameter of the uniform packed bed, coke free space, and impermeable zone bellow the taphole level. The taphole conditions dominate the total drainage rate under the terms of the assumed blast furnace conditions. The conditions of the peripheral region in the hearth determine the drainage rate patterns of the iron and slag. The peripheral region's permeability can be predicted from the drainage rate patterns of iron and slag, if precise measurement of the drainage rate patterns can be achieved. A drainage pattern, whether iron drains prior to slag or slag drains prior to iron, is largely affected by a drainage interval.

(cf. *ISIJ Int.*, **45** (2005), 1496)

Effect of FeO in dripping slag on drainage ability of slag

K.NISHIOKA et al.

Japanese iron and steelmaking industry has to re-

duce CO_2 emission by 11.5% in 2010 relative to the level of emissions in 1990. Stable blast furnace operation is required to reduce energy consumption and CO_2 emission in iron and steelmaking industry. For the stable blast furnace operation, precise controlled drainage is one of the important factors. However, there are many unrevealed phenomena in the hearth to perform the stable operation. Therefore, in this work, the effect of iron and slag dripping pattern, FeO concentration in the dripping slag on the iron and slag surfaces, thermal properties of refractory and brick on drainage temperature, temperature distribution in the hearth, temporal variation of iron and slag drainage rates and interfaces shapes were investigated by using tree-dimensional mathematical model.

The results indicate that more than 2 mass% FeO in dripping slag will cause deterioration of slag drainage ability due to high slag viscosity around tapholes. Continuous monitoring of FeO concentration in the tapping slag is effective to prevent deterioration of slag drainage ability. The trends of the other side of tapping taphole temperature were varied dramatically according with FeO concentration in the dripping slag. Even in the case of 0 mass% FeO in the dripping slag, there is a solidified slag near the hearth wall except around the tapholes. A peripheral distribution pattern will result in a stable drainage. Slag, which dripped on near the other side of the tapping taphole, stays around the taphole, and does not drain from the tapping taphole located opposite side.

(cf. *ISIJ Int.*, **45** (2005), 1506)

Effects of operation condition and casting strategy on drainage efficiency of the blast furnace hearth

T.NOUCHI et al.

A mathematical model is developed to quantify the effect of operation conditions and casting strategy on residual amount of slag and metal in hearth. The model is validated by a physical scale model experiment. Calculated results show that the residual amount of slag increases in proportion to the square of production. The effect of hearth permeability on the residual amount of slag is larger than slag viscosity. Then high permeability is necessary under high productivity operation condition. Although a load is not small, increasing tapping rod diameter and shortening cast duration are the effective way to decease maximum slag level. High durability filling mud is necessary to keep cast duration.

(cf. *ISIJ Int.*, **45** (2005), 1515)