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Technical Report

Latest Plant Engineering of Blast Furnaces

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Abstract

Nippon Steel Corporation is operating 13 blast furnaces (BFs), seven of which are large BFs having an inner volume exceeding 5 000 m^3. Various plant engineering technologies have been developed and commercially applied aiming at (a) higher flexibility for production increase, (b) reduction of total production costs through higher plant efficiency, stable operation, longer equipment life, labor saving, etc., (c) working safety, (d) environmental conservation, (e) disaster prevention, and (f) minimum equipment problems. Shaft staves and hearth bricks have been improved for extending BF campaign life, the change in the bosh profile minimized by inserting cooling plates/bars through the furnace shell, and high-accuracy, high-speed sensors introduced for stabilizing furnace operation. Top combustion hot stoves have been introduced, and blast temperature raised for BF efficiency improvement. Remote control and automatic operation have been applied to cast house equipment, and safety measures taken to prevent accidents by machine pressing/involving.

1. Introduction

Requirements for the operation of Nippon Steel Corporation's blast furnaces (BFs) include (a) higher flexibility for production increase, (b) cutting total production costs through improved plant efficiency, stable operation, longer equipment service life, labor saving, etc., (c) working safety, (d) environmental conservation, (e) disaster prevention, and (f) minimum equipment problems. Various plant engineering technologies have been developed and put into actual practice as the measures to attain these targets. The present paper describes the latest examples of BF plant engineering measures to extend equipment service life, stabilize BF operation, enhance the efficiency of hot stoves, and secure working safety on the cast house floor.

2. Latest Blast Furnace Engineering

2.1 Extension of BF campaign life

(1) Service life extension of shaft staves

After shaft staves (originally made of cast iron) were introduced from the then U.S.S.R., various improvement measures have been taken in terms of the material and the structure aiming at extending their service life to more than 20 years. The cooling capacity of the staves was improved for the 3rd campaign of Kimitsu No. 3 BF and the 2nd of Muroran No. 2 BF to extend the campaign life: the number of basic cooling pipes was increased from conventional six to nine by decreasing the intervals between them to less than 100 mm, the minimum manufacturable, and in addition to the intensive cooling water pipes at the upper and lower corners, a second serpentine pipe was provided on the back side. Aiming at improving the wall durability in the middle and lower shaft, where the heat load is high, to further extend BF campaign life, reduce the wall thickness and maintain the furnace profile in the long run for stable BF operation, copper staves were introduced for Kimitsu No. 4 BF (3rd campaign) in May 2003 as the first case in Nippon Steel. Thereafter, a horizontal rib protruding from the top edge toward the furnace inside was provided for each of the copper staves for the 3rd campaign of Oita No. 2 BF in 2004; it was meant for forming a thin stationary deposit layer of the furnace burden on the work surface to decrease the stave wear.

After that, to further extend the service life of copper staves by improving wear resistance, the number of ribs was increased so that the furnace burden deposit layers would form more easily. The effect of the ribs was confirmed through off-line tests, and the best pitch between them and their protrusion height was defined. To improve wear resistance and secure the effect for a longer period, hard-

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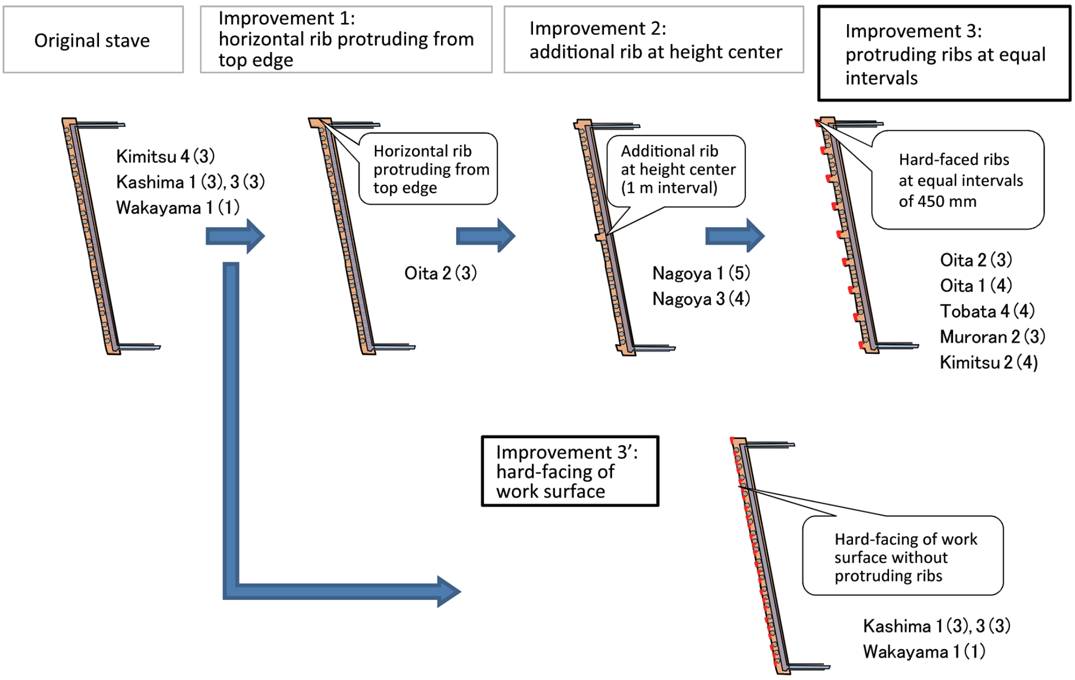

Fig. 1 Change of Cu staves for BF shaft

facing of the rib edge was proposed, and applied to real staves. **Figure 1** shows the change of the wear-resistance measures for the copper staves for BF shafts.

To develop specific wear-resistance measures for the copper staves, it was necessary to clarify the mechanisms of stave damage that occurred at the BF shaft. Damaged staves were examined in detail, scratch marks were found to run in the direction of the burden descent at the work surface, and sintered ore was found in the scratches as a result of chemical analysis using an electron probe micro analyzer (EPMA). This finding confirmed the need for hard-facing of the rib edge as a wear resistance measure (see **Photo 1**).

In relation to the formation of the stationary burden deposit layer, the effects of the rib structure on the burden descent behavior were estimated based on an off-line wear test using a 1/10 scale model and analysis by the discrete element method (DEM), and the optimum pitch and the protruding height of the ribs were defined. The off-line test clarified that the rib pitch with which the burden descent at the rib edge was slowest was roughly 40 mm, but the rate of the burden descent did not change significantly depending on the rib height. Based on these findings, we considered it possible to form the stationary burden deposit layer stably. Ribs 5 and 10 mm in height were compared at the test, and because there was no difference in the rate of burden descent between them, a rib height of 5 mm was considered sufficient (see **Fig. 2**).

To maintain the stationary burden deposit layer on the work surface for a long period, it is important to prevent the protruding ribs from wearing out, and for this purpose, the edges of the ribs were hard-faced. The durability of the hard-facing material was confirmed by an off-line wear test and trial use of ribbed staves on real blast furnaces.

In the off-line wear test, sintered ore and coke were made to slide repetitively on copper plate specimens at room temperature under a load equivalent to the furnace inside pressure. In addition to this, the wear of hard-faced sample staves was tested by inserting them into the shaft of an operating blast furnace, where the stave

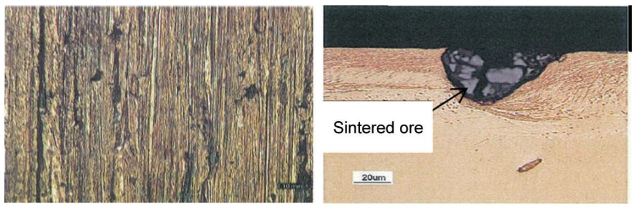

Photo 1 Work side surface of Cu stave

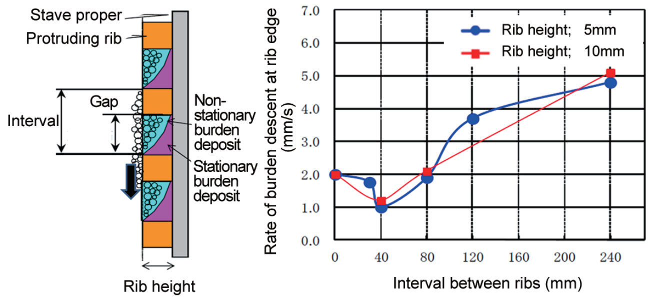

Fig. 2 Interval between protruding ribs

wear was fastest, some of them being water cooled and the others not; the test period was three months. When the sample staves were retrieved from the blast furnace, significant wear was found to have occurred in the specimens without cooling, but no such wear was seen with those cooled with water. This seemed to indicate that the hardness of the hard-facing material was kept sufficiently higher than that of the furnace burden when cooled. (see **Fig. 3**)

(2) Service life extension of hearth refractory

Most recently the BF campaign life is determined mainly by hearth refractory, or the bricks of the hearth wall and bottom. The service life of these bricks is defined mainly by the wear by erosion and breakage due to degradation and embrittlement. Various improvement measures have been taken in this regard; such measures are divided roughly into (i) those to improve hearth brick structure (brick work), and (ii) those to improve the brick material.

In addition, thanks to the latest advances of calculation technology to simulate phenomena inside the furnace, it became possible to take operational measures to extend the life of hearth refractory. Through a sensitivity analysis of the hearth structure to furnace operation conditions using a model, it has been clarified that the hearth brick erosion is greatly affected especially by the level of the dead-man coke at the furnace center. Through a comparison of the erosion of hearth bottom bricks between the case where the dead-man coke is immersed in the molten metal pool and another where it is floating on it, in the latter case, coke coating the hearth wall brick surfaces is locally lost, and there, the bricks are exposed to high thermal loads of the molten metal. The hearth portions where the thermal load is high coincide with those where the brick erosion is advanced (see **Fig. 4**).

The vertical position of the dead-man coke was calculated using analysis models, and the relationship between its immersion level and the distribution of actually measured temperature of hearth bottom bricks was examined, and a good correlation was found to exist between them. Based on this finding, technology to control the thermal load on the hearth bricks has been established, whereby the vertical position of the dead-man coke is controlled by changing the hot blast amount, its oxygen content, the coke ratio, etc. in the operation design and the daily furnace operation control.[1]

By adequately taking such furnace operation control measures, severe damage to the hearth wall and bottom bricks of Wakayama No. 5 BF was successfully prevented from aggravating, and the world's longest BF campaign record of 31 years was achieved as of the blow-off in 2019.

Thereafter, the brick structure of BF hearths began to be designed based on the analysis results obtained by combined use of different analysis models to decrease the hearth brick erosion.

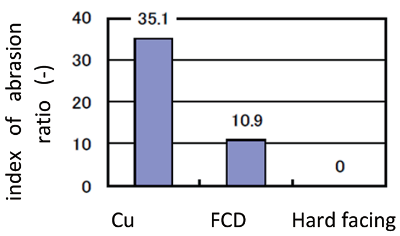

Fig. 3 Result of abrasion examination

2.2 Stabilizing furnace operation

(1) Stabilizing furnace profile by inserting cooling plates and bars above tuyeres

The profile of the BF bosh used to be designed using the inner surface of the bricks as the reference surface. However, the bosh profile changes significantly in terms of its angle and height when the brick lining is lost by wear. Through operation analysis of Kimitsu No. 4 BF (3rd campaign), for example, the in-furnace permeability and reducing agent ratio were found to deteriorate markedly after a year of operation, and at a boring investigation thereafter, the bosh bricks were found to have disappeared. **Figure 5** schematically shows the change in the bosh profile.

To confirm the influence of the profile change, the relationship between the bosh angle and the burden descent was examined using 3-D cut models, and the following findings were obtained:

(i) When the bosh angle is too steep, the formation of the pseudo-stagnant layer is insufficient, that is, the position of the root of the cohesion zone becomes unstable.

(ii) When the bosh angle is too shallow, the stagnant layer on the furnace wall becomes excessively large, which leads to unstable burden descent.

(iii) An optimum bosh angle exists somewhere between the above two situations, and there is an adequate relationship between the height and the angle of the bosh.

It is considered that unstable furnace operation is closely related to the progress of the damage to the bosh bricks, especially to the bosh profile, defined by its angle and height. As a measure to maintain an ideal bosh profile stably, cooling plates and bars were inserted through the lower bosh wall (see **Fig. 6**). BF operation performance was confirmed to have improved after their installation, and actually the bosh structure was stabilized, and the operation of the entire furnace as a consequence, thanks to the combined effects of the cooling plates and bars and the use of copper staves excellent in cooling capacity for the bosh.

The cooling plates and bars were installed closely above the tuyere line of Kimitsu No. 4 BF (3rd campaign) and Oita No. 2 BF (3rd campaign) anticipating that a stable pseudo-stagnant layer of the burden would form on the inner bosh surface in place of the bosh bricks that had been worn out.[2]

At a dismantling investigation after the blow-off of Oita No. 1 BF (3rd campaign), during which the cooling plates and bars had been installed, a furnace burden layer was found to have formed on the bosh wall covering the tips of the plates and bars. As the effects of the cooling plates and bars to stabilize the root of the cohesion zone and decrease the occurrence of tuyere damage were confirmed, their use was expanded to the BFs of the other works of the company.

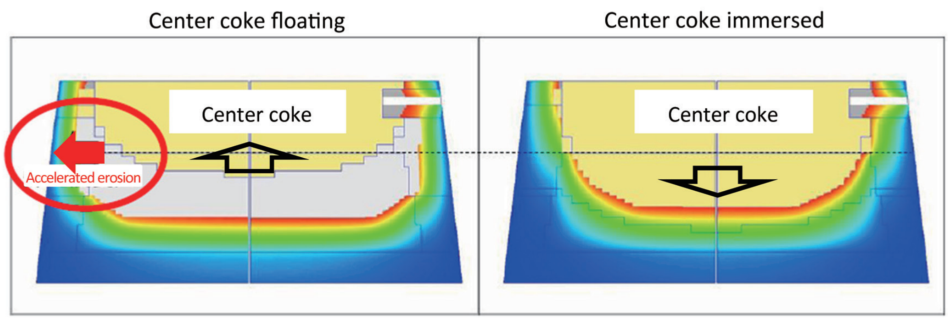

Fig. 4 Schematic illustration of hearth brick erosion

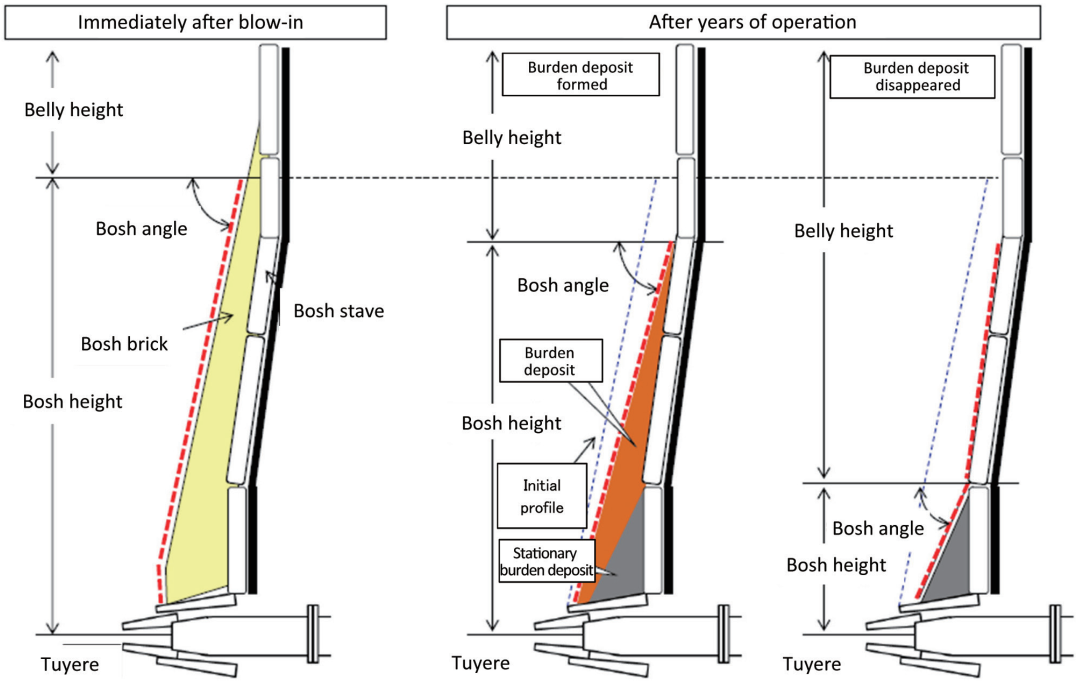

Fig. 5 Change of bosh profile

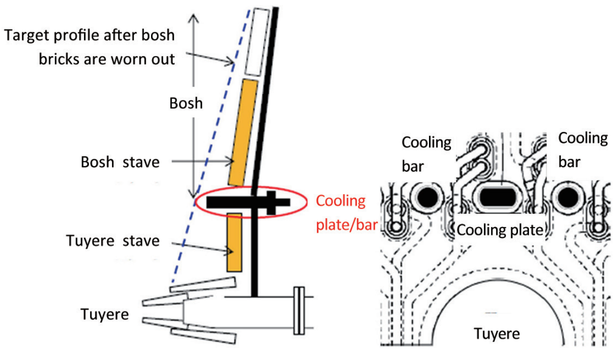

Fig. 6 Arrangement of bosh cooling plates and bars

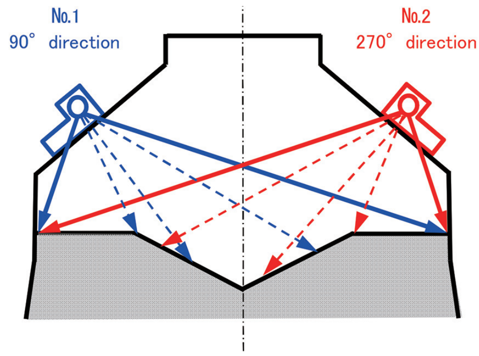

Fig. 7 Positions of burden profile meters

Based on the above, for future BF relining, the angle of the inner surface of the bosh bricks will be designed close to that of the bosh staves so that the bosh angle will not substantially change after the bricks are lost by wear, and the bosh stave angle will be maintained close to an ideal profile.

(2) Introduction of high-accuracy, high-velocity sensors

Blast furnace operation used to be controlled based on burden distribution presumed from the burden top surface shape in radial directions obtained by a probe-type profile meter and the position of the top surface detected by the sounding rods provided around the furnace throat. Since the probing of the conventional profile meter took time because it was necessary to insert a probe into the furnace inside, its use interfered with the burden charging schedule, and the measurement was performed only once per shift or so. It has been replaced recently by a pair of high-speed probe-less profile meters provided at opposing positions of the throat circumference.

To measure the position of the burden top surface, the new profile meters emit millimeter waves to scan the burden top surface without interfering with the charging chute; by this it is possible to visualize the burden top shape. As shown in **Fig. 7**, they are provided at two opposing positions of the furnace shell so as to cover all the burden top surface. The latest models incorporate improvements such as: (i) measuring time decreased to 1/3, (ii) smaller size and higher directionality of the scanning waves, and (iii) doubled detection accuracy of the burden surface quality. Through a function confirmation test on an operating blast furnace, the measurement of the new probe-less profile meters was confirmed to substantially agree with that of the conventional sounding system, and the new profile meters are being introduced to all the BFs of the company.

(3) Stabilization of checker bricks of hot stoves

Hot stoves are the equipment to heat the air to be blown into blast furnaces; a hot stove comprises a combustion chamber and a checker chamber, or a regenerator. In the combustion stage, the fuel gas is burnt through burners provided in the combustion chamber, and the high-temperature combustion gas is led to the checker chamber to heat the bricks for heat storage for heating the air in the succeeding stage; thus the checker bricks undergo repetitive temperature change. For this reason, they sometimes suffer damage, and it is necessary to repair and replace them while the damage is not too severe. However, because of the intensive light emission from the

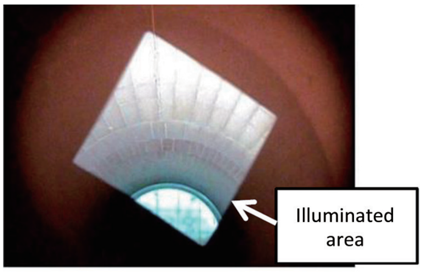

Photo 2 Photo of blast main inside taken with high-luminosity light source

bricks at high temperature, it is difficult to obtain clear images to monitor the inside of the stoves.

To solve the problem, a high-resolution camera and a special light source have been introduced to the observation apparatus for the hot stove inside. Thanks to a high-luminosity light source, clear images were taken at the inside of the hot blast main of Muroran No. 2 BF. As seen in **Photo 2**, even the brick joints are clearly visible.

2.3 Efficiency improvement of hot stoves

(1) Introduction of top-combustion hot stoves with metal burners

No. 3 Hot Stove for Kokura No. 2 BF entered into operation in December 2014; the new stove, which was erected by Nippon Steel Engineering Co., Ltd., is of a top combustion type having improved thermal efficiency. This type is excellent in mixed combustion, and is able to markedly decrease the emission of unburnt CO and NO_x. **Figure 8** schematically shows the structure of the top combustion type hot stove. Its main characteristics are as follows:

(i) Two metal burners are arranged so that the fuel gas and air blown through them form a swirling flow to heat the checker bricks evenly. The fuel gas and the combustion air are well mixed in the burners, and it is possible to decrease the emission of unburnt CO to virtually zero.

(ii) The fuel gas is almost completely burnt at the exit from the burner ducts to keep the dome at higher temperature than by conventional types; the equipment is compact because, different from conventional types, a separate combustion chamber is not required, and owing to the smaller surface area (roughly 90% of that of conventional types), the heat loss due to radiation from the stove shell is reduced.

(iii) A water-cooled shut-off valve is provided at the upstream of the metal burners, and it is possible to repair damage without having to stop the stove operation.

A second unit of this type of hot stove is being constructed for Nagoya No. 3 BF.[3)]

(2) Temperature increase of hot blast

The latest trend of BF operation is to aim at a low reducing agent ratio (decrease in CO_2 emission) and high productivity (t molten metal/day/m^3 inner volume); raising the temperature of hot blast is one of the approaches to meet these targets. The measures for raising hot blast temperature include: (i) increasing the number of hot stoves, (ii) raising the dome temperature of hot stoves, and (iii) increasing the amount of heat stored in the checker bricks by raising the combustion gas temperature, but each of these measures involve serious problems. Building an additional hot stove is not realistic because of space limitation and cost effectiveness, and raising the dome temperature is also difficult because it is likely to cause stress

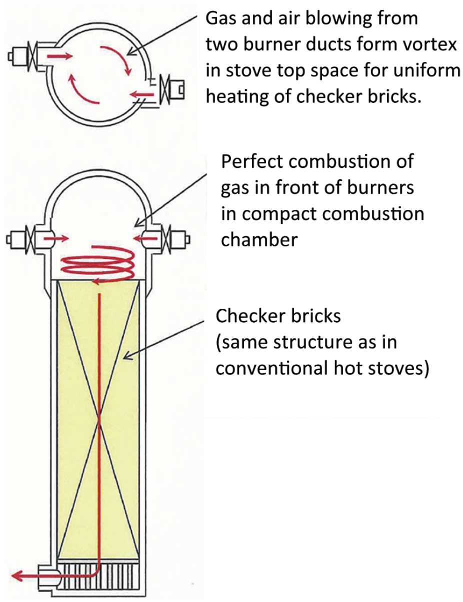

Fig. 8 Top combustion hot stove for Kokura No. 2 BF

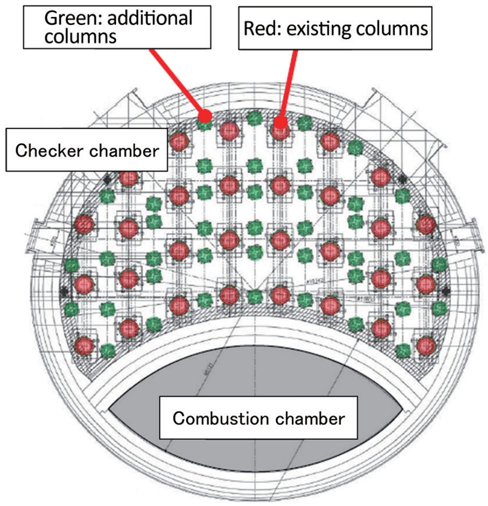

Fig. 9 Supporting structure of checker bricks (sectional view)

corrosion cracks of the steel shell. Raising the combustion gas temperature is similarly difficult because the metal support structures for the checker bricks are excessively heated and their strength falls, requiring their replacement with those of a more heat-resistant material. By changing the material of the support columns from conventional heat-resistant cast iron FCD400 to newly developed heat-resistant cast iron, FCD400H (supplied by Nippon Steel Engineering), increasing their number and reinforcing existing columns, it will be possible to raise the high-temperature creep strength of the support structures, and the combustion gas temperature by 100°C approximately.

To replace the support columns, however, it is necessary to remove the checker bricks supported by them and lay new ones. As a measure to avoid this and reduce the load on each column, we considered providing additional columns of FCD400H in the first place (see **Fig. 9**), and then reinforcing existing columns by wrapping them with outer pipes of FCD400H. By this it became possible to reinforce the brick support structure of existing hot stoves economically and within a short work period, and as a consequence, raise the hot blast temperature.

2.4 Safety measures for cast-house equipment

The work on the cast house floor of blast furnaces involves high muscular load in a high-temperature environment, and for working safety and securing labor force, it is urgently required to decrease or eliminate as much manual work as possible. It is also necessary to assess the risk involved based on internationally applicable standards and safety and health codes, and introduce safety design based on the relationship between personnel and machines at different life-cycle stages of equipment (erection, test run, commercial run, preparation, trouble shooting, and other related work) whenever facilities are newly built, revamped, or modified.

Such safety design mainly relates to the danger of workers being crushed by or trapped in moving machines. Studies are under way for eliminating the risk of such danger by thoroughly investigating the potential risks of existing equipment including automated facilities (mud guns, tap hole openers, etc.), developing specific safety measures, and installing facilities for them (such as safety fences and monitoring and alarm systems at entries to risk areas) while ensuring the workability of daily work (see **Fig. 10**). On the other hand, if operators are simply separated from moving machines, the work area may become limited and workability deteriorated. As a solution, forklifts are being introduced for safe and efficient materials transfer on the entire cast house floor (see **Fig. 11**).

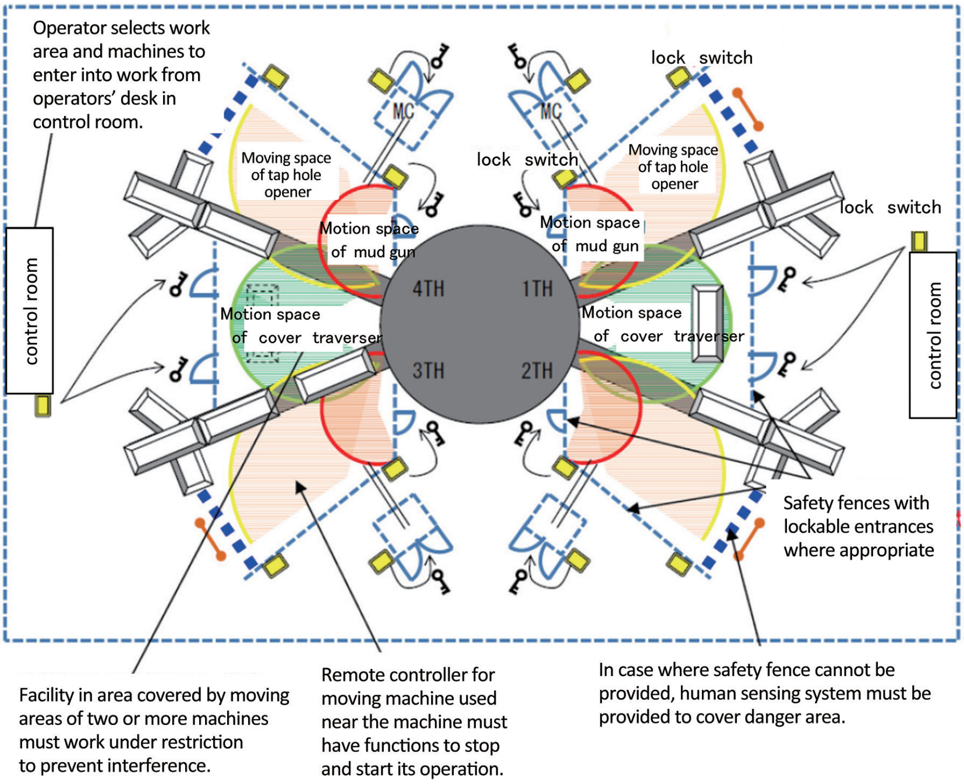

Fig. 10 Safety measures for machines on cast house floor

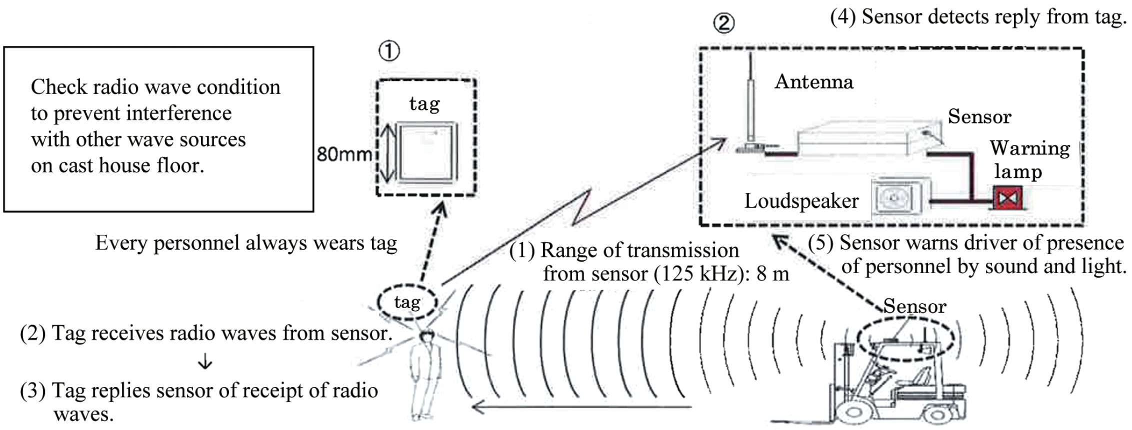

Fig. 11 Concept of personnel/vehicle separation on cast house floor

3. Conclusion

Nippon Steel's blast furnaces are required to attain (a) higher flexibility for production increase, (b) reduction of total production costs through efficiency enhancement, stable furnace operation, extension of equipment service life, labor saving, etc., (c) working safety, (d) environmental conservation, (e) disaster prevention, and (f) minimizing equipment problems, and various plant engineering technologies have been developed and put into actual practice to attain these targets. We are willing to continue improving blast furnace technology by developing equipment technologies that support further enhancement of blast furnace operation.

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