The Principle of Blast Furnace Operational Technology and Centralized Gas Flow by Center Coke Charging

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High pellets ratio operation forced by burden material restrictions at Kobe Steel resulted in the development of a center coke charging process based on centralized gas flow principle. This methodology produced a novel approach to burden distribution, coal combustion and pellets operation, in which these processes are viewed as part of a chain reaction. As a result of these developments, furnace performance has improved dramatically. This paper also describes future developments in blast furnace iron making.

Introduction

Kobe Steel started operation as an integrated steel manufacturing company with the blowing-in of the No. 1 blast furnace (BF) at the Kobe Works in 1959.[1] We, as latecomers, faced an issue with burden materials, which forced us into high pellet ratio operation requiring central gas flow. A reference is given in the "History of Central Gas Flow Principle".[2]

The centralized gas flow principle is based on the center coke charging.[3] This article overviews the effect of centralized gas flow principle on the enhancement of blast furnace functions, summarizes our blast furnace operations historically and technologically, and provides a view towards future blast furnace operation.

1. Milestones of our blast furnace operation technologies

Tamura categorized our history of pig-iron making into the following three periods, in an article submitted to this engineering report in 1984.[4]

- Phase I; commencement (furnace volume 600～1,000 m^3 : 1959～1970)
- Phase II; growth (furnace volume expansion period : 1970～1978)
- Phase III; ripeness (low growth period after energy crisis: 1979～1982)

Figure 1 shows milestones of our blast furnace

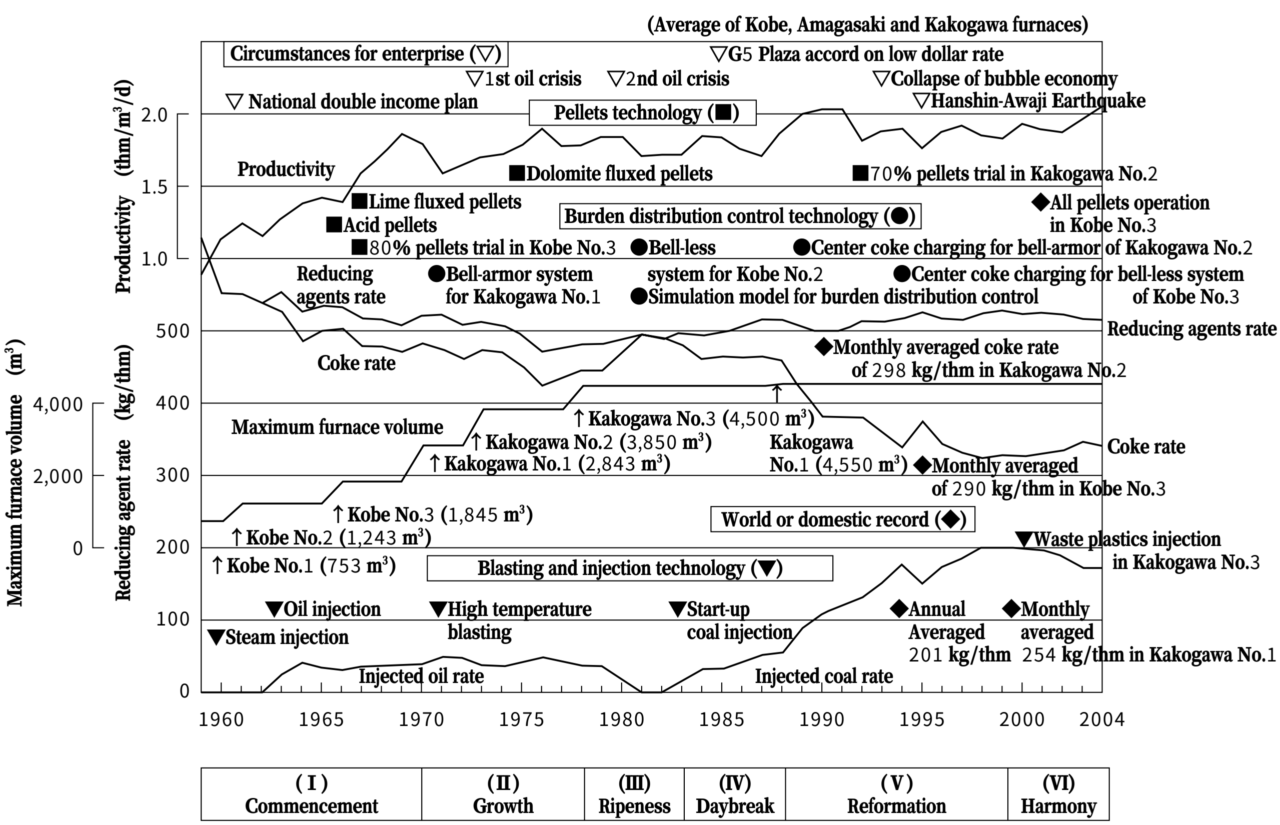


Fig. 1 Progress of blast furnace iron-making technology in Kobe Steel

operation. During the second period the volumes of #1, #2 and #3 blast furnaces at the Kakogawa Works, which were constructed after the #3 blast furnace at the Kobe Works, increased by 1,000 m^3. The Kakogawa #1 blast furnace, which led the way, was one of the first furnaces domestically to install a movable armor and the first domestically to install an in-furnace gas sampler, which served for the basic establishment of burden distribution control technology under high pellets ratio operation. The second period corresponds to the time in which the blast furnace technologies started to be systematized into an integrated engineering with the growth of furnace sizes.[5)]

In 1983 we started pulverized coal (PC) injection at the Kakogawa #2 BF and Kobe #3 BF to supplement the capacity of the coke furnace and to reduce energy cost. The PC injection adopted the concepts and theories of combining oxygen-rich blowing and fuel injection, each of which had been established by the 1970s. Subsequently, researches on the movement of burden materials in the furnace were conducted to overcome issues arising from the high pellets ratio operation at larger scale. Phase IV (daybreak: 1983〜1987) started with the advent of center coke charging, triggered by the strong desire to directly control the centralized flow. The history of our BF operation in the twenty years following Phase III is categorized into the following three phases.

- Phase IV ; daybreak (shift toward large amount PC injection: 1983〜1987)
- Phase V ; reformation (beginning of center coke charging: 1988〜1999)
- Phase VI; harmony (injection of waste plastics: 2000〜, all pellet operation 2001〜current)

The most important factor in determining the economical efficiency of fuel injection is the replacement rate of coke by substitute fuel. In the 1970s, theories of heavy oil injection were developed based on material balances, heat balances and equilibrium conditions. The general belief of the time was that a low coke ratio around 300 kg/thm (ton hot metal), which is calculated to be achievable by the increase of fuel injection of 0.3 kg/Nm^3 (dry air flow volume) in theory, may not necessarily be achieved in actuality.

In Phase V (beginning of center coke charging) that followed, we exploited the burden material control by center coke charging, and the combustion technologies of heavy oil and PC using double lances simultaneously. This led the Kakogawa #2 BF to achieve a monthly coke ratio of 298 kg/thm (PC ratio 123 kg/thm, heavy oil ratio 62 kg/thm) in April 1990; the first time in the world to achieve less than 300 kg/thm.[6), 7)] At the end of the month, the lowest coke ratio achieved was 289 kg/thm (PC ratio 128 kg/thm, heavy oil ratio 65 kg/thm). It is very noteworthy that we achieved coke ratio less than 290 kg/thm.[8)]

2. Background and significance of the center coke charging technology[9)]

Figure 2 (a) shows a schematic diagram of blast furnace interior. In order to operate a blast furnace stably and economically, it is important to form an inverse-V shaped, cohesive zone in the high

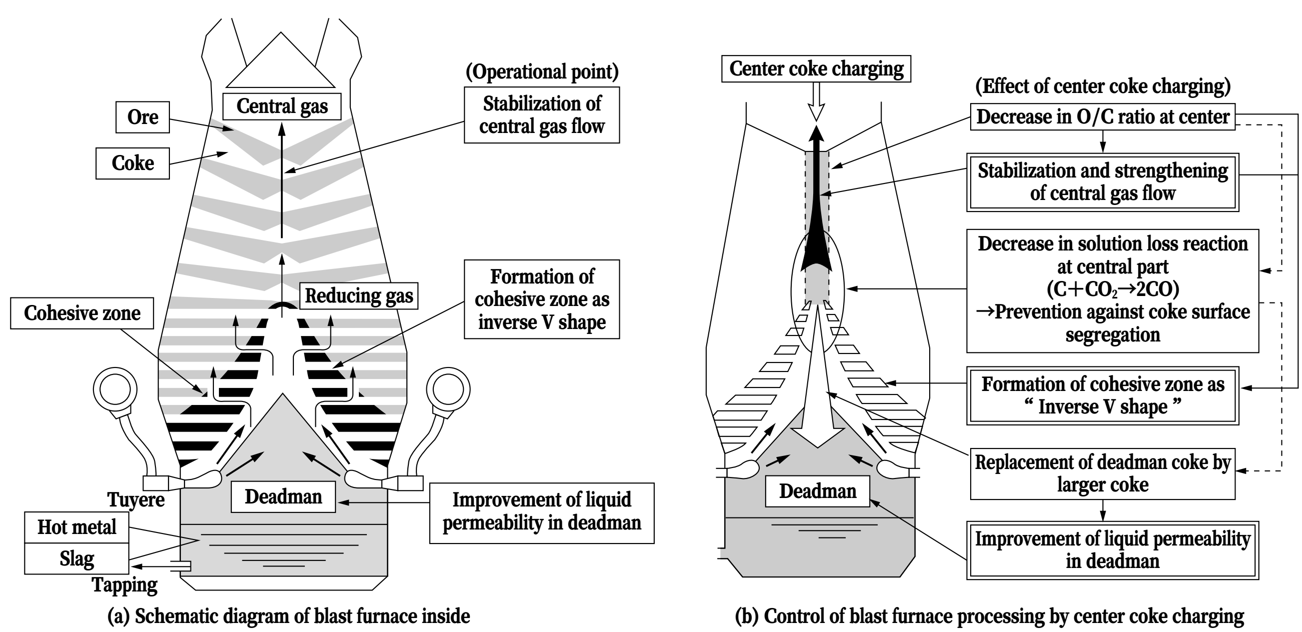


Fig. 2 Control of blast furnace processing by center coke charging

temperature region, by locally intensifying the gas flow at the center of the furnace. To achieve this, the ore to coke weight ratio (O/C) has to be maintained lower locally at the center. This is done by adjusting the weight ratio of ore and coke around the radius at the time of charging both the materials from the top of the furnace.

In the conventional method, however, it was difficult to maintain the O/C at the center low enough due to the effect of charging, such as the flow-in of coke and changes in ore sizes. Increased ore volume at the center lowers the gas permeability and reduces center gas flow making the cohesive zone W shaped. This leads to increase of heat-loss at the furnace wall and disturbs the descending of burden materials, deteriorating the furnace wall. Many furnaces have mechanisms for adjusting the charging positions of materials to control O/C distribution. The mechanisms include armor plates placed around the periphery of the furnace throat, and rotating chutes with angle adjusting capabilities, however, the area of their control is limited to the periphery. There has been a need for a method of controlling the gas flow at the center of furnaces in an easy and reliable manner.

Another issue is that lower portions of blast furnaces contain "deadman" coke of which permeabilities for gas and liquid affect the performance and life time of the furnaces significantly. Especially, the deadman coke determines the flow of gas and hot metal in the lower portion of a blast furnace, and deterioration of the gas permeability increases gas flow along the furnace wall, resulting in W-shaped cohesion and poor furnace conditions.

At the furnace bottom, where molten pig iron is held, low liquid permeability at the center of deadman coke develops annular flow of the melt at the time of discharge, causing erosion of the refractory wall and shortening the life of the furnace body. It is desirable to improve the liquid permeability of the deadman coke to lengthen the life of the furnace, however, this has been considered to be difficult since the deadman coke is at the bottom of the furnace and is heated higher than 1,500℃.

Figure 2 (b) is a schematic showing control of blast furnace processing by center coke charging. The coke layer has a gas-flow resistance smaller by a factor of 10 compared to that of the ore layer and has a high gas-permeability. When a larger amount of coke exists, relatively, at the center of a blast furnace, the high temperature gas, consisting mainly of CO generated at the tuyeres, concentrates at the furnace center and distributes through the coke layer of the cohesive zone to the periphery. The coke in the furnace, during its descending process, is subject to the carbon solution loss reaction (CO_2+C →CO) by CO_2 gas generated by reductive reaction of the ores. If the coke undergoes excessive amount of this reaction, it becomes porous, weak in strength and generates a large amount of powder. Especially when the deadman coke goes through this reaction, it bring a large amount of powder into the deadman, deteriorating its gas and liquid permeability.

Center coke charging, on the other hand, reduces ore volume and CO_2 generation in the center, suppresses the carbon solution loss reaction and makes the deadman coke healthy with less powder. This improves the liquid permeability of the deadman and allows the melt to flow through the center of the furnace bottom at the time of discharge. In other words, the center coke charging reduces the annular flow and prevents temperature rise of the bottom side wall.

3. Action and achievement of the centralized gas flow principle in the burden distribution control technology

During the Phase IV (daybreak), we experienced lowering of gas temperatures in the upper shaft at the center to the intermediate area with the increase of the PC rate. This led to a drastic increase of the amount of solution loss carbon. **Figure 3** shows the loss of central gas flow due to the solution loss reaction. Usually the change in gas temperature distribution in the throat precedes the change of furnace temperature by 6～10 hrs. This is due to the fact that the higher O/C for the increased PC rate reduces the descending velocity of burden at the furnace wall[6], resulting in the flow-in of pellets mixed ore toward the center of the furnace. According to a measurement conducted prior to the blow-in[10], the formation of mixed layer at the O/C boundary is confirmed to be more enhanced at the center of the furnace than at the wall. The pellets tend to segregate at the time of charging, infiltrate to the bottom of the ore layer and penetrate the ore layer to reach the coke layer at the middle to center area of the furnace. For the high O/C ratio accompanying the high PC rate, it is important to stabilize burden material distribution in the radial and height direction by preventing formation of the mixed layer and subduction of pellets.

Figure 4 shows the progress of burden distribution control for intensive coal injection.

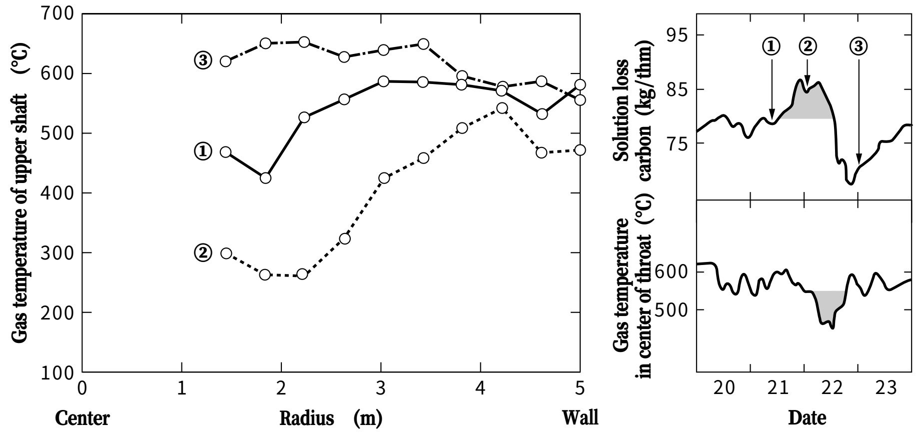


Fig. 3 Loss of central gas flow before changing of solution loss reaction

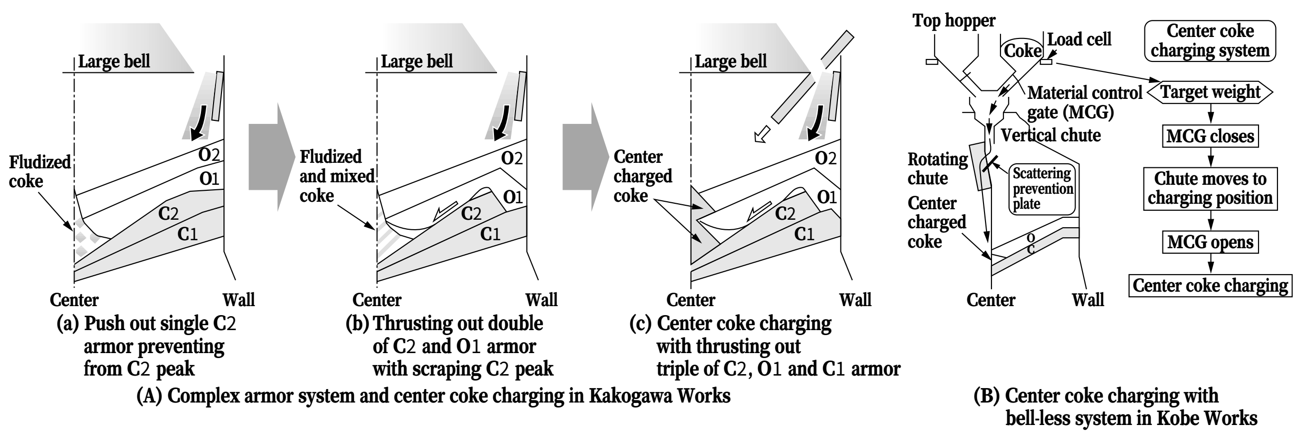


Fig. 4 Progress of burden distribution control for intensive coal injection at Kobe Steel

During Phase IV (daybreak) in the bell-armor method (4 batch charge; C1 ↓ C2 ↓ O1 ↓ O2 ↓) (Figure 4 (a)) of the Kakogawa Works, the layer thickness ratio between ore and coke (LO/LC) was maintained high by the push-out of the C2 armor so that the LO/LC at the center became relatively low, promoting formation of fluidized coke at the center and maintaining the centralized gas flow (Figure 4 (a)). In the early Phase V (reformation) a ridge line (peak) of C2 layer was formed by further push-out of the C2 armor and then the peak was scraped off by the following O1 charge by the push-out of O1 armor. As a result, the LO/LC distribution in the intermediate to the peripheral area became uniform and the mixed layer was pushed toward the center, reinforcing the fluidized coke at the center. This was the beginning of complex armor control (Figure 4 (b)).[11)]

During this Phase V (reformation) the center coke charging[3)] (Figure 4 (c)) has been developed as a direct controlling method that relies neither on fluidized coke nor mixed layer. The method employs a special chute which charges coke directly at the center after charging of C2 and O1 layers and thus controls the centralized gas flow directly. As a result, the armors are used dedicatedly for the peripheral control (Operation concept I). The peripheral control by C2 and O1 armors hits a limit when the peripheral thickness of the C2 layer becomes so large that the C1 layer becomes exposed. The test operation of 250 kg/thm PC rate[12)] described later employs a direct control of the peripheral LO/LC by the C1 armor.

In Phase IV (daybreak) the bell-less method at the Kobe Works (2 batch charge; C ↓ O ↓) (Figure 4(b)) focused on the LO/LC control at the periphery by forming a "flat" on the coke layer. In the early Phase V (reformation) a complex control of the coke flat and ore flat was employed, as in the case of the bell armor, to prevent breakdown of coke at the time of charging.[13)] The distribution control was aimed at the prevention of breakdown of coke and the approach may seem to be reversed from the one for the bell-arm method. This was due to the fact that sintered ores used at the time made the maintenance of centralized gas flow rather easy, the coke peak was made smooth by tilting of the rotating chute, and that the coke layer thickness was prioritized because the charging quantity of coke (coke base) was limited due to the limitation in the capacity of top hopper. The bell armor method which scrapes off the coke layer surface and the bell-less method which build up smooth layer of coke are different in their approach; however, both the methods have been developed for the same purpose of making the LO/LC distribution smooth in the intermediate to peripheral region.

The Kobe Works experienced deterioration of metal and slag discharging due to increase of fine coke in the deadman in the past low coke ratio operation. In Phase V (reformation) bell-less coke center charge method[14] has been developed as a high level control method of the furnace center. Due to the limitation of coke base described above, a center coke charge system has been developed which has a capability of charging a measured amount of coke at the center at the end of charging by tilting the rotary chute almost to the perpendicular.

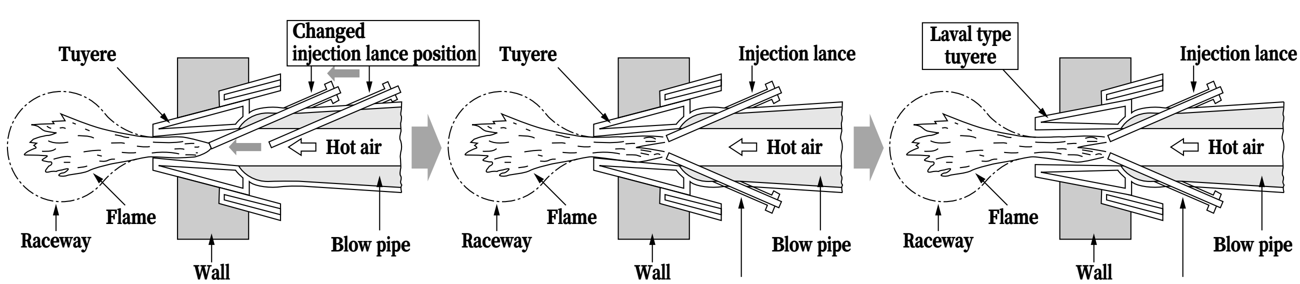
4. Action and achievement of the centralized gas flow principle in the powder coal combustion technology

In the Phase IV (daybreak) when the PC injection started, the PC injection position was placed in the blow pipe for the concern of lower combustion ratio compared to heavy oil injection. **Figure 5** shows progress of coal injection system for intensive coal injection. The injection position was then moved toward the tuyere to reduce the pressure loss and variation at the tuyere[15] (Figure 5 (a)). In the intensive coal injection, even the raceway combustion is controlled by the diffusion of PC and the combustion rate tends to lower. The double lance method[16] was introduced to supplement this for the first time in Japan (Figure 5 (b)). Lately a PC combustion control[17] by a new Laval type tuyere with double lances has been developed to prevent pressure loss and vibration at the tuyere and to promote the raceway combustion (Figure 5 (c)).

Unburnt coal powder (unburnt char) generated in the raceway is considered to be consumed by the carbon solution loss reaction in the furnace and affects the gas flow in the furnace significantly. **Figure 6** shows a result of a two-phase flow model simulation[18] on the hold up of unburnt char. Unburnt char tends to accumulate at positions where large changes in gas flow occur, and accumulates especially at the lower portion of the cohesive zone. In case of W-shaped cohesive zone, this will increase the flow in the periphery. The cohesive zone has to be maintained in an inversed V shape. In other words, an inverse V shaped cohesive zone provides a zone for unburnt char to gasify and supplements the raceway function of PC combustion (Operation concept II).

The Kakogawa #2 BF achieved a monthly coke ratio of 298 kg/thm (PC rate 123 kg/thm, heavy oil ratio 62 kg/thm) in April 1990 in the simultaneous injection of PC and heavy oil by exploiting the burden distribution controls by center coke charge and enhanced raceway combustion by double lance.

The technology of intensive PC injection was completed through Phase V (reformation) and by the end of 1990s. In March 1998 the Kakogawa #1 BF achieved PC rate of 254 kg/thm.[12] During this increase of PC rate from 200 kg/thm to 250 kg/thm, the replacement ratio was dropped and, as a result, the coke rate remained to be 291 kg/thm. This is considered to be due to fine coke generated by abrasion in the shaft being exhausted out of the furnace by increased shaft gas flow.



(a) Altenation of combustion position of single lance into tuyere for preventing from back pressure

(b) Double lance injection system for intensify combustion in raceway

(c) Laval type (convergent divergent) tuyere with double lance system for high volume blasting

Fig. 5 Progress of coal injection system for inensive coal injection at Kobe Steel

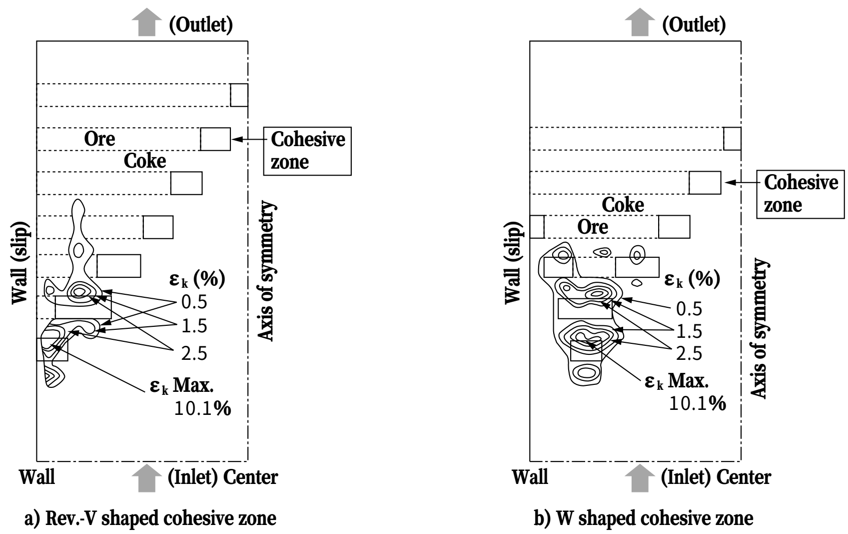


Fig. 6 Calculated results in total hold up of unburnt char around cohesive zone

5. Action and achievement of the centralized gas flow principle in the longer operating life and restart operation

Our operation is based on the centralized gas flow control by center coke charge, which reduces heat load and its variation to the furnace and ensures stable operation with prolonged operation life. **Figure 7** shows countermeasures and repair for extending furnace life. At the hearth bottom, in addition to the maintenance of deadman cokes for higher liquid and gas permeability, the depth of the tap hole has to be maintained to prevent circumferential flow of hot metal caused by the free-space formation behavior.[19] Reduction of production and cessation of blowing are the most effective measure; however they impact on the production level. Increase of TiO_2 in the charge and choking of tuyere affects the full scale production. Repair of the shaft is based on the guideline for shaft repair[20], which is derived from solid flow analysis. Blow-in TiO_2 from the tuyere[21] is used for localized melt-down at the furnace bottom. The furnace bottom determines the life of the furnace because of its difficulty of repair.

Figure 8 shows comparisons of hearth profiles before blow-in and after blow-out. The Kakogawa #2 BF (second), which blew out in 1996, operated at a low coke rate of 330 kg/thm (PC rate 150 kg/thm, mort coke rate 55 kg/thm) even right before the blow-out. The minimum wall thickness of the #2 BF (second) was 1,000 mm with good condition of the bottom and thicker than that of the Kakogawa #3 BF (first) which was 835 mm.

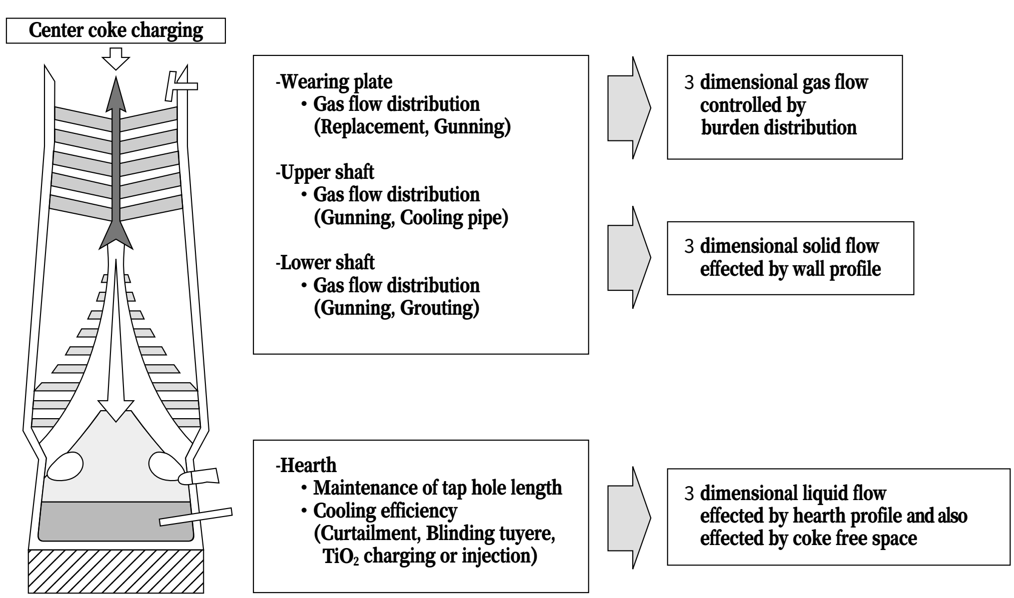


Fig. 7 Countermeasures and repair for elongating furnace life taken by Kobe Steel

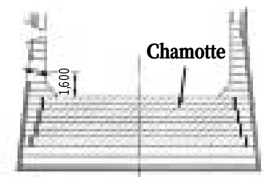
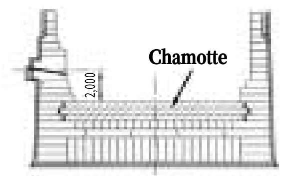
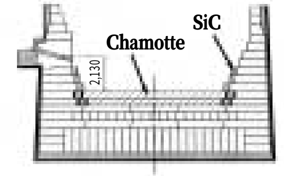
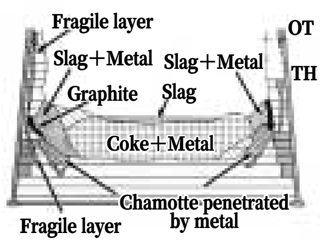
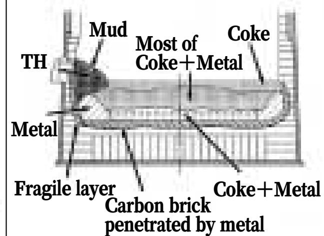
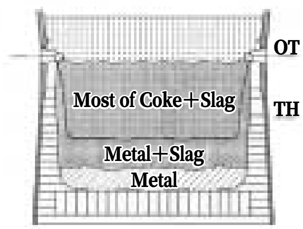
BF (IV)	#2 -1st (3,850 m³)	#3 -1st (4,500 m³)	#2 -2nd (3,850 m³)
Ope. period	5Y - 2M	10Y	16Y - 2M
Production	13,207 kt (3,430 t/m³)	28,998 kt (6,444 t/m³)	41,790 kt (10,855 t/m³)
Initial hearth profile			
Hearth profile blown out			
Minimum wall thickness	500 mm	835 mm	1,000 mm

Fig. 8 Comparison of hearth profiles before blown in and blown out

There was no damage to the cooling pipes of the stave indicating the advantage of center coke charging.[22)]

The restart of the Kobe #3 BF after the unexpected shutdown by the Great Hanshin-Awaji Earthquake in 1995 is still fresh in our memory. Since there had been no precedent for restarting a blast furnace once shut, the restart provided a big challenge to our technical group. The furnace was established for center coke charge by bell-less method in Aug. 1993. The operation after the restart went smoothly and operation at low coke rate continued. In Oct. 1995, seven month after the restart, the BF achieved a domestic record of 296 kg/thm which was renewed by the same BF to 290 kg/thm in Jan. 1996[14)] (The BF also achieved a domestic record of 294 kg/thm in the biannual coke rate average from Oct.1995 to March 1996). A detailed account of the seventy five days of activities before the restart blow-in is reported in ref. 23, including the digging out of the burden materials of 2,090 tons.[23)]

6. Action and achievement of the centralized gas flow principle in the pellet utilization technology

Control of the cohesive zone is affected not only by the burden material distribution but also the softening and melting characteristics of ores. The ores need to remain in the state of agglomerate packing at higher temperatures. The preferable characteristic of a burden is to have agglomerate packing up to higher temperatures and to have a narrow temperature zone between the beginning of softening and melting. Pellets have undesirable softening behaviors due to reduction retardation. We have developed dolomite-fluxed pellets with improved high temperature characteristics.[24)] In order to maintain agglomerate packing of ores, 1,100℃ reduction contraction under load is applied for the control of hot pellet conditions.

Figure 9 shows the correlation between

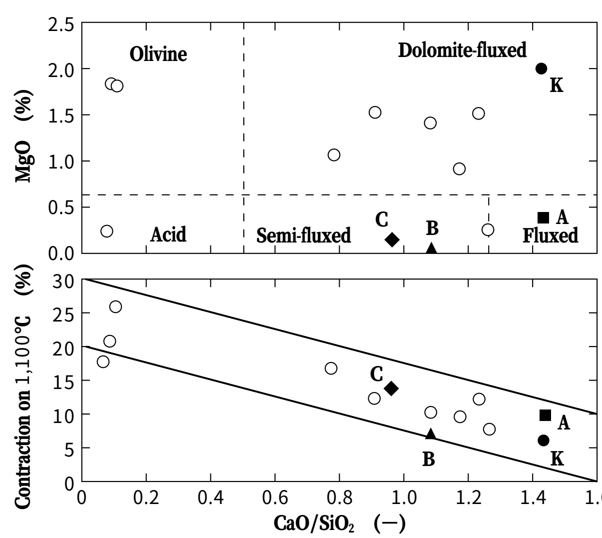


Fig. 9 Correlation between composition of various commercial pellets and reduction contraction under load

composition of various commercial pellets and reduction contraction under load. Our dolomite fluxed pellets (K) have lower contraction compared to imported pellets (A,B,C) and are more suitable for maintaining the agglomerate packing up to higher temperatures.

Our high pellets ratio operations were demonstrated by the 80% ratio test operation at the Kobe #3 BF in 1967[25] and by the 70% ratio test operation under intensive PC injection at the Kakogawa #2 BF in 1991.[26] Especially the 70% ratio test operation at the Kakogawa #2 BF developed a concept of pellets operation with center coke charging. The reduction retardation phenomena can be improved by the formation of thermal reserve zones in the periphery as a result of center coke charge allowing central gas flow and PC injection lowering the heat flow ratio. The shape control of cohesive zone by centralized gas flow can accept the reduction retardation phenomenon which is an inferiority of pellets, by enhancing the reductive reaction by the thermal reserve zones in the periphery (Operation concept III).

The Kobe #3 BF (third) (furnace volume 1,845 m^3, blow-in April 5, 1983) after the restart from the earthquake recovery in 1995 started to use outsourced pre-treated ores and pellet, because of the shut-down of the sintering factory in May 1999. The BF started all-pellets operation (pellet 73%, ore agglomerate 27%)[27] in Sept. 2001. The increased amount of pellets reduces the decline angle of ores and a greater amount of ore flows to the furnace center, suppressing the centralized gas flow. The reduced decline angle also reduces the flat area of ore stack in the periphery obstructing the descending action. The inversed V shape of cohesive zone in the all-pellets operation has been maintained by the increased amount of center coke charging and maintenance of flat area of ore and coke stack in the periphery.

In the all-pellets operation, it is also necessary to prevent the enlargement of the root of cohesive zone which is caused by the mixed use of pellets with low alkalinity. To improve the reduction retardation phenomenon by center coke as described above, it is required to keep the pellets concentration in the periphery below 30% in case up to 50% pellets ratio and the acid pellets concentration in the periphery below 30% in case above 50% pellets ratio form the softening and melting characteristics of the pellets. This concept has led to the development of the pellets time-series discharge control.[27]

Figure 10 shows the transition of Kobe #3 BF on ferrous burden constitution in selected blast furnaces from Europe, Japan and USA. The Kobe #3 BF has shifted to all-pellets operation successfully while maintaining low sintered ore constitution. The transition to all-pellets operation has been ensured by the developments of the center coke charging and operation technologies by grades of pellet. The stable operation of the furnace and its environment-conscious nature are highly evaluated.[28]

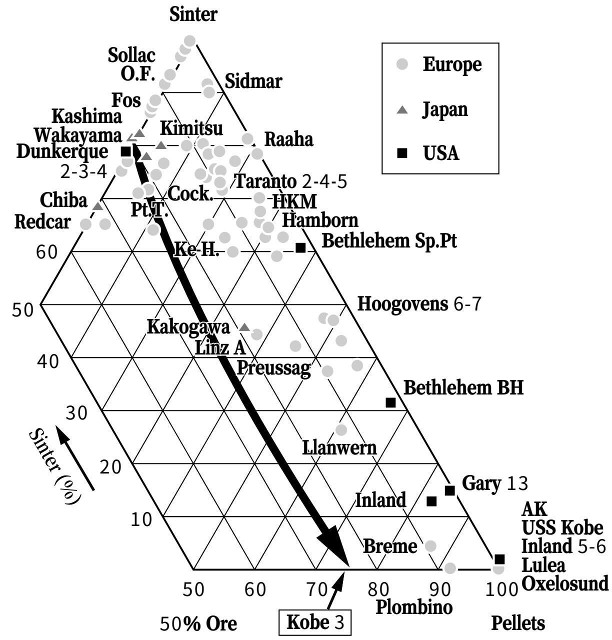


Fig.10 Transition of Kobe No.3 blast furnace on ferrous burden constitution in selected blast furnaces from Europe, Japan and USA

7. Future blast furnace operation technology based on the centralized gas flow principle

The following two points are the subjects in our blast furnace operation.

Firstly, the currently operating Kakogawa #1 BF (third) has been operating under the PCI since early days after the blow-in and local damages of stave pipes in the bosh (B2) and lower shaft have become noticeable since 1999.[29] This is considered to be due to the increased heat burden of the shaft caused by the up-rise of the cohesive zone level and to the increased sensitivity (instability) of gas flow to the variation of the burden material grain sizes. More precise control of peripheral flow will be required for this.

Secondly, the coke utilization has to be tightened for the lower reductant ratio operation in the future. **Figure 11** shows the effect of coke and coal rate on solution loss reaction load (coke reaction load) and coke fine generation in deadman of blast furnace.[12] Although the deterioration of

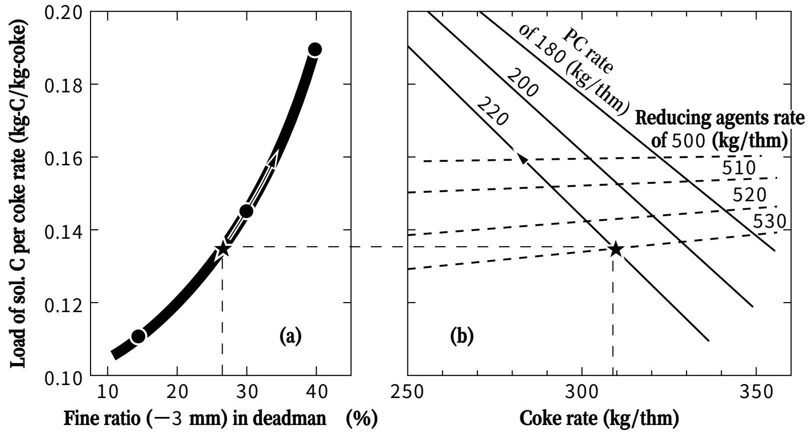


Fig.11 Effect of coke and coal rate on solution loss reaction load and coke fine generation in deadman of blast furnace

the deadman coke reaction can be prevented by the center coke charge, coke fines generated by the coke reaction in the intermediate to periphery area penetrate into the deadman through the deadman surface.[30] As a result the coke reaction load in increased with the decrease of coke ratio when the PC ratio is constant increasing coke fines in the deadman (Figure 11 (b)). In order to operate at a lower reductant ratio, further improvement of gas and liquid permeability of the deadman coke is required for the increased coke fines.

Conclusions

The steel industry will move toward higher value added products in the future. In order to support the value added steel products, iron sources have to be secured with stable operation of furnaces. Environment consciousness, including CO_2 reduction, leads more toward lower reductant ratio operation. The centralized gas flow principle needs more advancement to satisfy both these requirements.

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