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Trend of Ironmaking Technology in Japan after 2000

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Abstract

The first two decades of the 21st century were turbulent for the steel industry. The reorganization of the steel industry across borders has progressed and the increased demand for steel products has caused a rise in the price of raw materials such as iron ore and metallurgical coal. Furthermore, more emphasis has been placed on global environmental protection and carbon dioxide emission control than ever before. The ironmaking technology division in Japan has struggled to cope with these changes both at home and abroad. This report describes the trend of the development and commercial application of the ironmaking technology of Japan in the first two decades of the 21st century.

1. Introduction—Situation of Japan's Ironmaking after 2000

Soon after the rapid valuation of the Japanese yen brought about by the Plaza Accord in 1985, the blast furnace operators of Japan took business streamlining measures and eliminated their blast furnaces one after another. Then in the 1990s, the Japanese steel industry was forced into tough times facing sluggish demand resulting from the breakdown of the bubble economy and further valuation of the currency. At the same time, the industry was pressed to respond to the new problems of global warming and waste disposal.

After 2000, raw material suppliers as well as steelmakers were reorganized one after another, redundant production facilities were shut down all over the world, and as a result, major iron ore suppliers were reorganized into three giant groups, namely Vale, Rio Tinto, and BHP-Billiton, responsible in total for 70% of the global market. On the other hand, Arbed (Luxemburg), Aceralia (Spain), and Usinor (France) merged together in 2002 to form Arcelor, which then merged with Mittal Steel in 2006 to form Arcelor Mittal, the largest multinational steelmaker in the world. In Japan, likewise, Nippon Kokan (NKK) and Kawasaki Steel merged together to form JFE Holdings, Inc. in 2002, and then in 2012, the then Nippon Steel and Sumitomo Metal Industries merged to form Nippon Steel & Sumitomo Metal Corporation (the name was changed to Nippon Steel Corporation in 2019).

The world steel demand grew rapidly in the 2000s thanks to the economic expansion of the BRICs (Brazil, Russia, India, and China) and other countries. As a result, world crude steel production in 2017 grew to 1 690 million metric tons (Mt, all the units herein are metric), more than twice that before 2000. In this situation, the supply of high-quality iron ore and coking coal was suddenly considered as a bottleneck, and their market prices became highly volatile over the last few years depending on the supply-demand balance (see **Fig. 1**).[1)]

In contrast, the production amounts of pig iron and crude steel of Japan have remained substantially unchanged over the last 20 years except for a temporary and significant slump in the aftermath of Lehman's fall, and owing to stagnant domestic steel consumption, the ratio of steel exports is higher than in the 1990s.

In this situation, the efforts of the ironmaking technology division in Japan have turned to the measures to secure a superior position in the international market, and have focused on the development and commercial application of measures for productivity enhancement for further cost reduction, extension of the service life of production facilities, increased use of economical low-quality raw material brands to cope with rising market prices, environmental protection, and reducing energy consumption.

It was in 2006, 13 years ago, that the present Technical Report last dedicated an edition to ironmaking technology,[2)] and later in 2011, there was an article that reviewed the trend of this field of technology.[3)] Eight years has passed since, and the present article examines the outlines of ironmaking technologies developed and put into commercial practice in Japan after 2000, mainly those after the special edition in 2006. (Note that when specific steel works are mentioned herein in relation to technical development and application, they are referred to by the present names). As for the details of individual ironmaking technologies of Nippon Steel, the readers are kindly requested to refer to the relevant articles in this especial edition. The Iron and Steel Institute of Japan (ISIJ) celebrated the 100-

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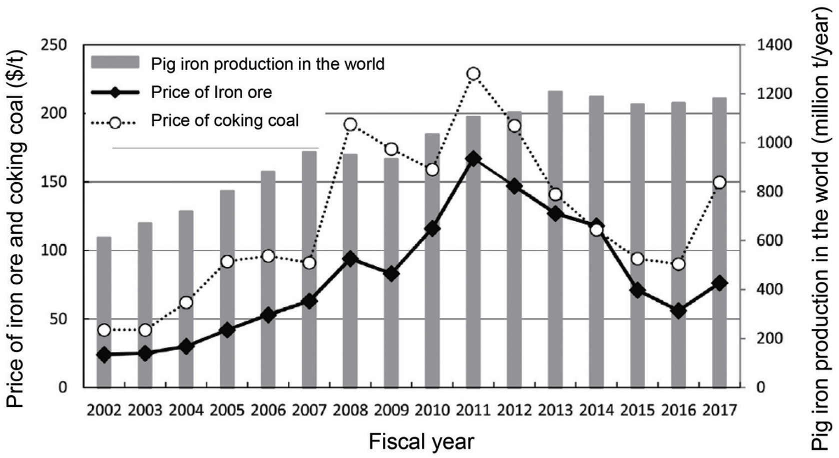

Fig. 1 Trends of world pig iron production and prices of iron ore and coking coal

year anniversary of its foundation in 2015, and as a commemoration, published a special edition of Tetsu-to-Hagané for the 100th anniversary.[4–6] In addition, the proceedings of the 217th and 218th Nishiyama Memorial Technical Conferences[7] include papers on the development and commercial application of the technologies that markedly changed the ironmaking practice of Japan. The readers are also invited to refer to these publications.

2. Outstanding Technologies Commercially Verified or Applied after 2000

Principal technologies commercially verified or applied in Japan after 2000 in the fields of blast furnaces (BFs), iron ore treatment and sintering, and coke making are listed, respectively, in **Tables 1**, **2**, and **3**. The items on the lists were selected from among the subjects published in CAMP-ISIJ, the proceedings of technical conferences of ISIJ, and the years and the pages in the reference literatures are those written in the relevant proceedings and abstracts. Note that the tables do not exhaustively cover all the technologies commercially verified or applied during the period.

Thanks to the advances in measurement and calculation technology, a wide variety of sensing and simulation methods have been put into daily practice of blast furnace operation. Various measures to improve the quality of sintered ore have been developed for improving blast furnace operation; such include the decrease in reducing agent consumption taking advantage of the effects of BF burdens such as reactive coke agglomerates (RCA) to lower the temperature of the BF thermal reserve zone, the high-ratio mixing of coke in ore layers, and injection of natural gas to lower the reducing agent ratio. Pellets and reduced iron are also charged into commercially operated blast furnaces. In the field of agent injection through tuyeres, technology and facility development for mass injection of pulverized coal (PC) were encouraged, and tuyere injection of converter slag has been commercially practiced. Different techniques have been developed and actually applied for extending BF campaign life. Various ore agglomerating methods and function improvement of the BF charging chute have been practically introduced aiming at enhancing readiness for the changing availability of natural resources and productivity improvement. In the fields of environmental conservation and energy saving, new measures such as injection of hydrocarbon gas into sintering machines and reduction of NO_x emission by CaO-modified coke fine (LCC; lime coating coke) have been devised and put into daily practice. As for coke making, the SCOPE21 oven, which is the product of a 10-year national technical development project launched in 1994, has been put into commercial reality. On the other hand, while new coke ovens were built and old ones padded up, a variety of methods for oven observation, diagnosis, and repair have been developed, and actually used as countermeasures against the super-aging of coke ovens. Noteworthy examples of such technologies are outlined below.

3. Developed and Commercially Applied Blast Furnace Technologies

3.1 Monitoring and prediction of in-furnace processes

The techniques for directly and scientifically observing and predicting the processes inside BFs have shown significant advances lately. In relation especially to the phenomena during the transport and charging of BF burdens, tests on a 1/3 scale model and simulations[8–10] on real BFs by the discrete element method (DEM) have been conducted (those shown in **Fig. 2**, for example), and based on these, various simulation methods for predicting burden distribution have been devised and commercially used. Material flow is being measured in some BF raw materials systems using radio frequency identification (RFID) tags widely used for logistic management.[11]

Since it is very difficult to directly see the inside of an operating blast furnace, efforts have been concentrated on the development of mathematical models that can express the process behavior inside a real blast furnace.[12] As a consequence, three-dimensional non-steady-state mathematical models that take into consideration the materials flow, heat transfer, and reactions inside the furnace, models that express the BF burden layer structure (see **Fig. 3**),[13] those to predict the refractory wear and erosion of the hearth bottom and side wall, and DEMs for raceway evaluation[14] have been devised, and actually employed for improving operation efficiency and extending furnace life. Attempts have also been made to directly observe the inside of an operating furnace using muons of the cosmic ray.[15, 16]

In addition, visualization and analysis of BF operation data to assist the furnace operation have shown remarkable progress, and the technology to collect data and visualize what takes place inside the furnace has been practically applied. In consideration of the difficulty to directly see inside the furnace, 3D-VENUS, a data processing system capable of displaying in-furnace data three-dimensionally second by second (see **Fig. 4**),[17–19] was introduced to Nippon Steel's Nagoya Works in 2007; the system employs roughly 500 units of temperature sensors provided on the cooling staves and 20

Table 1 Examples of developed and commercially applied blast furnace technologies

Classification	Technology
Sensing and prediction	High temperature thermocouple (2000 Kakogawa) EMF (electromotive force) sensor (2004 Kimitsu) 3D-VENUS (3 Dimensional Visual Evaluation and Numerical analysis System of blast furnace operation) (2008 Nagoya) Tracking of burden materials by using RFID (Radio Frequency Identification) (2010 Kashima) Observation of the inside of BF by cosmic-ray muon (2011 Nagoya, 2013 Kimitsu) Simulation of blow-in operation by discrete element method (DEM) (2014 Kimitsu) Continuous melted iron and slag temperature measurement (2013 Muroran) Tuyere camera (2015 Kimitsu) Online estimation of cohesive zone shape (2016 Kurashiki) Prediction method of gas channeling (2017, 2018 Kakogawa)
Burden materials	Large-amount charging of small-size sinter (2002 Fukuyama) High MgO (dolomite) sinter (2003 Kashima) Sintered ore coated by lime stone and coke breeze (2005 Kurashiki) $CaCl_2$ coating sinter for RDI improvement (2008 Kimitsu) Low-basicity sintered ore (2009 Kokura) All pellets operation (2002 Kobe) High DRI (Direct Reduced Iron) ratio operation (2001 Nagoya) RCA (Reactive Coke Agglomerate) (2012, 2016 Oita) High DI coke and high RI sinter (2003 Yawata) High reactivity coke (2003 Muroran)
Burden distribution	Flat burden distribution (2000 Fukuyama) Mixed coke charging, FCG (Flow Control Gate) dynamic charging (2005, 2008 Chiba) Center coke charging (2006 Kakogawa) Mixed nut coke charging (2007 Kakogawa, 2015 Keihin) Supporting system for controlling burden distribution (2007 Kashima) Application of DEM simulation to burden distribution control (2014 Kimitsu)
Tuyere injection	Low VM (high CVL (Calorific Value in Lower part of BF)) coal for PCI (2004 Muroran) Higher steam coal ratio in PCI (Kakogawa 2014) High PCR at low blast temperature (2001, 2002 Fukuyama) Convergent and divergent tuyere (2007, 2014 Kakogawa, 2013, 2014 Kobe) High dispersive lance for PCI (2004 Fukuyama) Flux added waste plastics injection (2005 Fukuyama) NG (Natural Gas) injection (2006, 2013 Keihin) Converter slag injection (2015 Kobe) Adjustment of unbalance of PCI (2017 Oita)
Productivity	High productivity (2.3) operation (2000 Mizushima) High productivity (2.3) and low RAR (460) operation (2002 Kimitsu) High productivity (2.3) and low CR (323) operation (2004 Kakogawa) High productivity (2.56) operation (2013 Keihin) Low productivity (1.2) operation (2009 Kokura)
Facilities	Extension of BF campaign life (2005 Wakayama, 2018 Chiba) Whole casting repair at main runner in hot condition (2000 Wakayama) Wet type gunning to BF throat (2001 Wakayama) Carbon block with high corrosion resistance (2003 Kimitsu) Long period shutdown for stave replacement (2005 Nagoya, 2005 Kakogawa, 2006 Kure, 2016 Muroran) Design of new hot stove with mathematical model (2008 Kashima) Bosh cooling bar (2016 Kimitsu)
Relining	Relining and blow-in operation (2000 Nagoya, 2002 Kokura, 2002 Mizushima, 2004 Kimitsu, 2005 Oita, 2005 Keihin, 2005 Kashima, 2006 Fukuyama, 2007 Fukuyama, 2008 Kashima, 2009 Kobe, 2013 Fukuyama) Additional tap hole (2009 Muroran)
Others	Desiliconization in hot metal runner (2012 Kobe)

or so units of shaft pressure sensors to detect the in-furnace burden condition and gas flow. The advanced information technology (IT) using accumulated data, artificial intelligence (AI), and deep learning has shown dramatic advances lately,[20] and the fruits of such progress are expected to further advance BF operation technology.

3.2 Lowering reducing agent ratio

Actual application of the technology to decrease the consumption of reducing agents through temperature control of the thermal reserve zone of BFs has shown remarkable advances as a measure to significantly lower the reducing agent ratio.[21] An example of its

Table 2 Examples of developed and commercially applied sintering technologies

Classification	Technology
Granulation	Capacity enhancement of HPS (Hybrid Pelletized Sinter) (2001 Fukuyama) Lime stone and coke breeze coating granulation (2005 Kurashiki) RF-MEBIOS (Return Fine Mosaic Embedding Iron Ore Sintering) (2009 Wakayama) P type separate granulation process (2010 Wakayama) APD (Anionic Polymer Dispersing agent) (2010 Yawata) Semi-pellet process (with roller press and polymer dispersant) (2013 Yawata) Double layer magnetite mini-pellet (2017 Kakogawa) Micro-particles binder addition (2017 Wakayama)
Low SiO_2 sinter	Low SiO_2 sinter (2000 Fukuyama) Dolomite sinter (2003 Wakayama)
Charging, feeder	Coke upper charging (2001 Kakogawa) Double air segregation feeder (2001 Oita)
Capacity enhancement	Stand-support sintering (2002 Kimitsu, 2016 Nagoya) Capacity enhancement of sintering machine (750 mm height) (2011 Oita) Pallet width extension (2002 Chiba)
Environment and energy saving	Hydrocarbon gas injection (Super-SINTER) (2012 Keihin) Improvement of waste gas recirculation system (2010 Kakogawa) Two-stage combustion burner with high velocity (2018 Kurashiki) Recovery system of cooler waste gas (2000 Kashima) Circular hopper cooler (2016 Wakayama) LCC (Lime Coating Coke) (2013, 2014 Oita)
Other	Paper sludge addition (2002 Kakogawa) Visualization system of sintering machine (pallet wind leakage monitoring system etc.) (2011 Kimitsu)

commercial application is the use of reactive coke agglomerates (RCA),[22–24] or unfired pellets of a mixture of carbon sources and iron sources (see **Fig. 5**). Pellets of carbon sources and iron sources such as dust formed on a disc pelletizer are charged into blast furnaces as a raw material without firing. In this form, the carbon and iron sources are adjacent to each other, and the carbon components begin to gasify readily at low temperatures, which lowers the temperature of the thermal reserve zone and improves the efficiency of reducing reactions inside the furnace. It was commercially applied at Nippon Steel's Oita Works in 2012, and using RCA containing 20% carbon, a reducing agent consumption decreasing effect of 0.36 kg-C/t-HM (hot metal) has been obtained per 1 kg/t-HM of carbon in RCA.

The development of hybrid composite iron ore was also promoted;[25] this is another type of iron ore agglomerate formed in heat; it takes advantage of the thermal plasticity of coal, and exhibits reducing agent ratio lowering effects like RCA. The production process of another type of iron-carbon agglomerate, ferro-coke, is being developed at present (see sub-section 6.2 hereof).

When much coke is mixed in the BF ore layers, melting contraction of the ore in the cohesive zone is expected to decrease, the void ratio kept unchanged, and as a result, in-furnace gas permeation is improved. This operation method was commercially introduced to No. 6 BF of JFE Steel Corporation's East Japan Works Chiba,[26–28] whereby sintered ore and coke are discharged simultaneously from the two bunkers at the furnace top and charged into the BF by inversed charging, that is, to suppress burden segregation the charging chute angle is controlled such that the burden lands at the furnace center at the beginning of a charging batch and is spirally expanded towards the periphery in a funnel shape. In addition, dynamic material flow control technology is employed to control the flows of the ore and coke from time to time using flow control gates to improve the mixing of coke; this proved effective at decreasing the reducing agent ratio.

In addition, the injection of a high-hydrogen concentration reducing agent, natural gas (consisting mainly of CH_4), has been put into regular operation at No. 2 BF of JFE Steel's East Japan Works Keihin;[26, 27] it has been found that high-H reducing gas accelerates reducing reactions and maintains the voids of the cohesive zone, greatly improving the gas permeability in the lower furnace portion.

3.3 High pellet charging

Tests of 70% pellet charging were conducted at No. 2 BF of Kobe Steel, Ltd.'s Kakogawa Works, and based on the results, No. 3 BF of its Kobe Works began all-pellet operation (73% pellet + 27% lump ore, no sintered ore).[29] There, maintaining gas flow along the furnace center line by center charging of coke and low heat flow ratio operation by pulverized coal injection (PCI) proved promising to prevent reducing reactions from slowing down. To maintain the mixing ratio of low-basicity pellets in the furnace peripheral regions at 30% or lower, time-series discharge control of pellets has been developed and commercially employed.

3.4 Agent injection through tuyeres

Various technologies have been developed in relation to the tuyere injection of pulverized coal in large amounts, and as a result, double lances have been used for combustion control, and de Laval type tuyeres (also called the CD tuyeres) for minimizing the pressure loss in the tuyeres and pressure fluctuation and stabilizing combustion in the inside of the raceway.[29] In addition, Kobe Steel's Kobe Works began to inject converter slag into the BF to lower the slag viscosity in the "bird's nest" deep inside the raceway, to facilitate slag dripping and improve gas permeability,[30] and the coke ratio has been decreased thanks to gas flow thus improved.

On the other hand, as the coal injection amount increased, there arose a problem of increased deposit of fine coke on the surface of the dead-man at the furnace center. To further decrease the reducing agent ratio, it is essential to keep the dead-man permeable to gas,

Table 3 Examples of developed and commercially applied cokemaking technologies

Classification	Technology
Coal pre-treatment	SCOPE21 Pre-treatment (2008 Oita, 2013 Nagoya) CMC (Coal Moisture Control) (2017 Keihin)
Construction and pad-up	SCOPE21 type coke oven (2008 Oita 2013 Nagoya) Construction of new battery (2006 Fukuyama, 2010 Wakayama, 2012 Kashima, 2017 Kashima) Pad-up (2008 Muroran, 2012 Muroran, 2017 Chiba, 2017 Kurashiki) Optimum design of coke oven heating-up burner (2018 Kimitsu)
Hot banking	Hot banking operation (2013 Yawata, 2016 Nagoya)
Repair of coke oven chamber	Hot repair of the middle part of oven chamber (2001 Mizushima, 2010 Kashima) Hot repair of the end part of oven chamber (2001 Mizushima, 2007 Kimitsu) Coke oven chamber wall diagnosis and repair machine; DOC (Doctor of Coke Oven) (2002, 2006 Oita, 2009 Kimitsu) Repair of damaged hole in the center of coke oven chamber wall using DOC (2014 Kimitsu) Repair by CVD (2003 Fukuyama) Ceramic welding machine (2005 Kakogawa, 2007 Kurashiki) Repair equipment for upper end part of oven chamber (2007 Sakaide) Welding machine on the oven top (V-CRM) (2013 Kakogawa)
Observation of coke oven chamber	Mobile chamber width measuring system (2001, 2002 Kakogawa) Coke oven chamber observation device mounted on the pusher (2006 Kakogawa) Coke oven chamber width measuring device mounted on the pusher (2008, 2009 Kakogawa) Coke oven chamber wall monitoring system (2011 Kakogawa) 3D measurement of coke oven chamber wall (2018 Sakaide)
Repair and observation of combustion chamber	Observation and repair equipment of combustion chamber (2001 Yawata) Observation equipment of regenerator (2009 Kashima) Observation equipment of combustion chamber (2005 Kakogawa, 2013 Kurashiki) Repair of combustion chamber (2013 Kakogawa)
Other repairs	Repair of waste gas duct (2008 Wakayama) Repair of butterfly valves in waste gas duct (2008 Sakaide) Dry main renewal (2001 Muroran, 2008 Nagoya, 2014 Kitakyushu, 2016 Chiba) Profile determination of CDQ chamber with 3D laser scanner (2014 Kashima)
Operation and facilities	Improvement in automatic coke oven operation (2000 Oita) Coke oven operation support system (2000 Chiba) Waste gas circulation combustion system (2002 Yawata) DRG (Dilute Rich Gas) (2016 Yawata) Sliding combustive device on top of the ascension pipe (2009 Wakayama)
Carbon deposition control	Carbon deposition control by atomized water injection into oven free space (2001 Muroran) Carbon removal lance (2008 Kashima) Carbon control unit (Carbon Incineration Revolution) (2011 Nagoya, 2014 Oita, 2018 Kimitsu)
Environment	Cleaning equipment for charging hole (2003 Kashima) Detector of gas leakage from coke oven doors (2006, 2007 Kakogawa) Coke oven door monitoring system (2010 Kakogawa) Dust monitoring system by β-ray (2009 Sakaide) New coke oven door sealing system (2013 Kakogawa)
Recycling, etc.	Waste plastic recycling (2001 Nagoya, 2018 Wakayama) Genetic analysis of activated sludge (2009 Kakogawa)

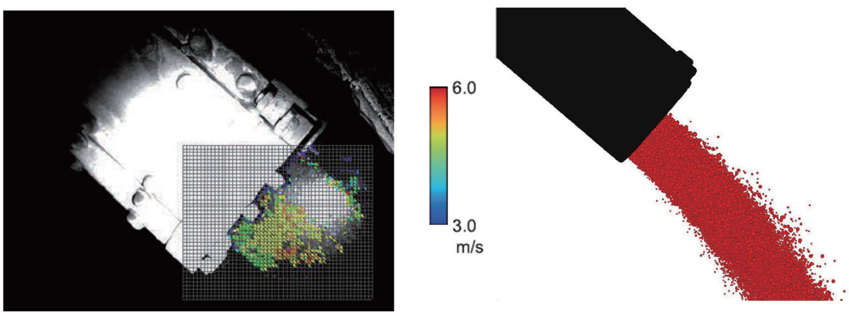

Fig. 2 Sinter particle discharging velocity field analysis by PIV and snapshots of sinter particle discharging behavior simulated by DEM

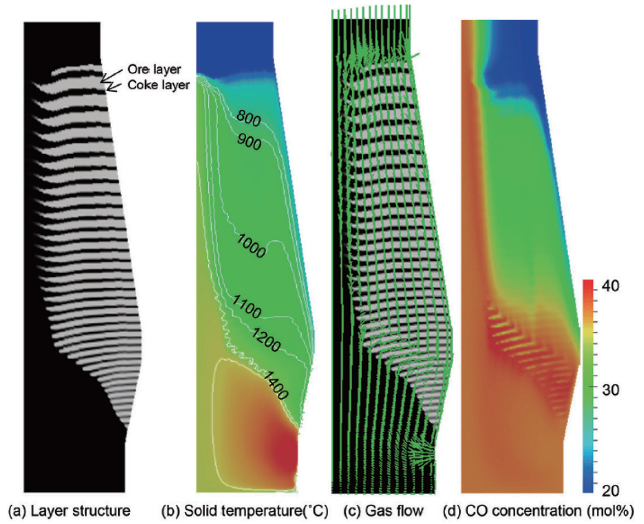

Fig. 3 In-furnace states calculated by mathematical blast furnace models

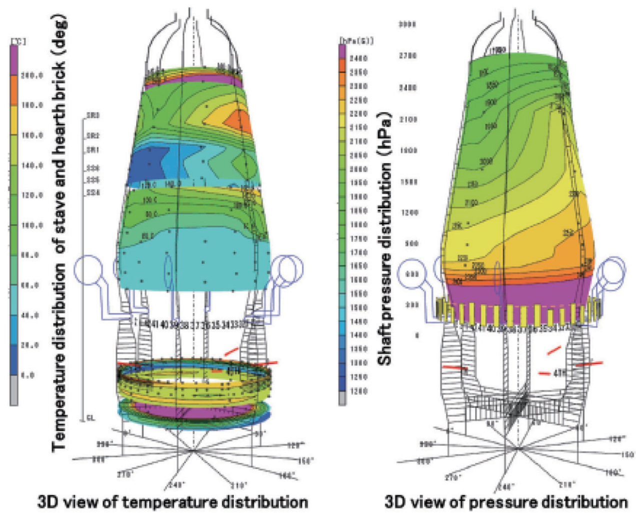

Fig. 4 Examples of display by 3D-VENUS

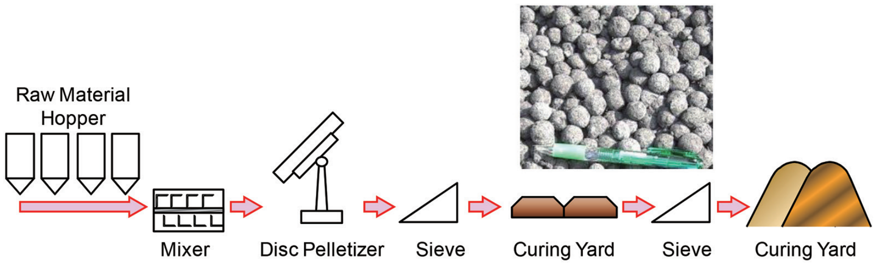

Fig. 5 Appearance of RCA and process flow of RCA production

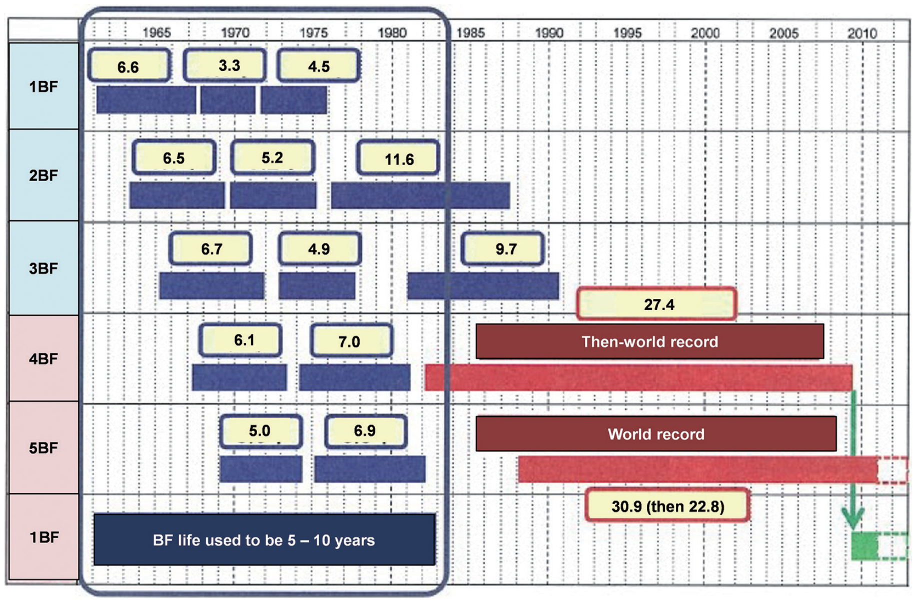

Fig. 6 BF campaign lives at Wakayama Works

molten metal and slag, and as such, burden distribution control and adequate use of different raw materials and reducing agents will become increasingly important.

3.5 Extension of BF campaign life

A wide variety of technologies to extend BF campaign life have been developed and put into commercial practice. Nippon Steel's Wakayama No. 4 BF matched the then world record of the longest uninterrupted operation of 10001 days (roughly 27 years and 4 months) till the blow off in July 2009 (see **Fig. 6**).[31] Later, Wakayama No. 5 BF renewed the campaign life record by working for as

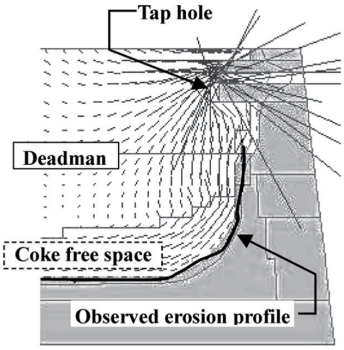

Fig. 7 Estimated and observed erosion profiles

long as 11289 days (30 years and 11 months) from February 22, 1988 to January 18, 2019.[32] These records were attained thanks to the combination of technologies such as (1) a newly developed stave changing method, (2) wear and erosion control of hearth bricks (see **Fig. 7**),[33] and (3) advanced simulation technologies. These technologies will be expanded to other works to further extend the BF campaign life.

4. Developed and Commercially Applied Technologies of Iron Ore Treatment and Sintering

4.1 Measures against change in iron ore quality and technology for productivity enhancement

Exploration conditions of iron ore resources of the world are changing significantly. In terms of quality, while different people view the situation differently, I would like to point out in the first place the increasing ratio of fine ore as a serious problem. The increase of fine ore leads to a decrease in the pseudo-particle size of sinter feed, which hinders the permeability of the ore bed on the sintering pallets, and as a result, lowers the plant productivity. Of the widely varied methods for improving the permeability of the ore bed, some examples of granulation methods actually applied are presented below.

A composite granulation sintering method named mosaic embedding iron ore sintering (MEBIOS) was proposed, whereby hard and coarse grains, roughly 10 mm in size, are distributed partially in the ore bed to secure voids for permeability. As a practical variation of the method, the return fine MEBIOS (RF-MEBIOS) has been commercially introduced to Nippon Steel's Kashima No. 3 DL (standing for the Dwight-Lloyd sintering machine), Wakayama No. 5 DL, and Kokura No. 3 DL.[34, 35] By this process, coarse return sintered ore grains roughly classified at a damper are led to a by-pass route and mixed with the pelletized sinter feed coming from a mixer/pelletizer (see **Fig. 8**). By this it is possible to increase the moisture of the sinter feed to strengthen the pellets, and secure the voids between the ore grains thanks to higher frictional force between grains due to the addition of dry sintered ore. As a result of the combined effect of the two, the ore bed permeability is improved and the sintering productivity has been improved by 4%.

As measures to cope with the increase of fine ore that is difficult to granulate, ore granulation methods using fine particles as the binder[36–38] have been developed and commercially employed.

One of them is the method of granulation on the SPExII line, a forming line for high-strength coarse grains (semi pellets); the method consists of the processes of dry crushing by a roller press and fine particle dispersion using polymer dispersant (organic binder)[36] (see **Fig. 9**). By this, ultra-fine particles, 10 μm or less in size, are dispersed with the polymer dispersant in voids between fine ore grains, and rearranged during drying to exert a strong bonding force. It has been commercially operated at Nippon Steel's Yawata Works since 2008, and proved to be an effective measure against lowering quality of iron ore.[3, 39]

Another example is the granulation method using fine particles crushed in a vertical wet ball mill as the binder.[37, 38] By this method, ultra-fine-particle binder in slurry, which is prepared by crushing iron ore in water to suspend the grains, is added to fine ore so that it fills the voids between ore grains, which enables forming of strong agglomerates without requiring expensive dispersants (see **Figs. 10** and **11**). This method has been introduced to Nippon Steel's Wakayama Works, and by mixing 13.3% fine ore, sintering productivity has been improved by 2.4%.[30, 40]

JFE Steel has commercially employed a method of producing ore agglomerates coated with lime stone and fine coke.[27] The method is characterized by charging lime stone and fine coke into a drum mixer from the discharging end to have them coat pseudo grains mainly of iron ore.[41] By this process, it is intended to improve the reducibility of sintered ore by coating the pseudo grains with lime stone and thus having highly reducible primary hematite retained in quantities in the sintered ore. It is also intended to raise the sintering

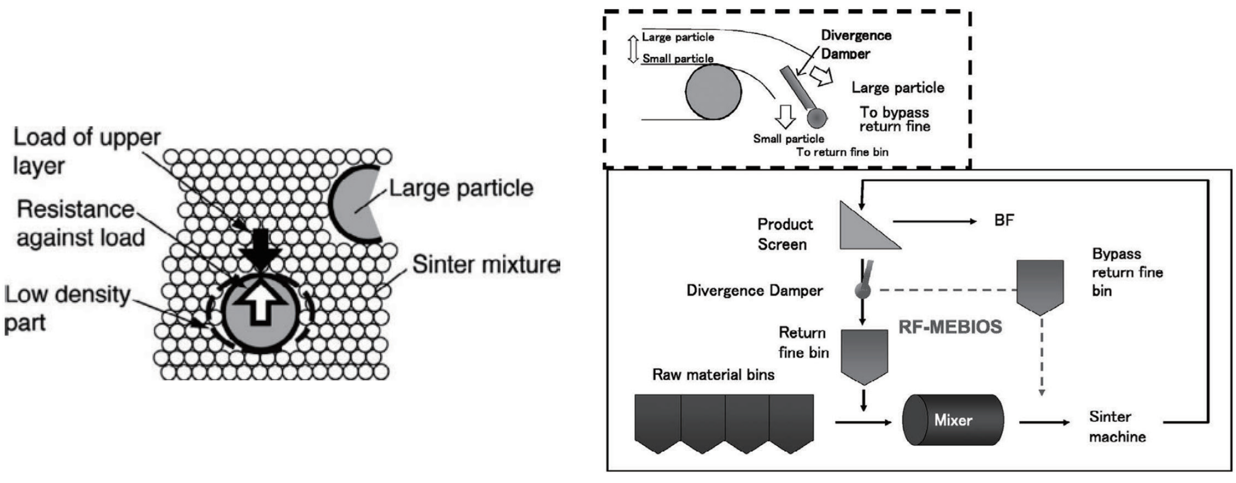

Fig. 8 Concept of MEBIOS and process flow of RF-MEBIOS

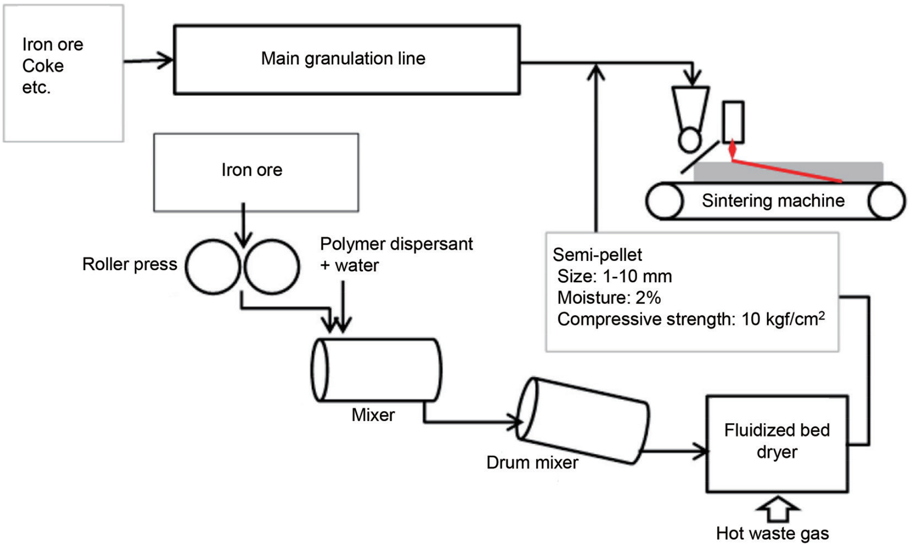

Fig. 9 Granulation process flow by using roller press and polymer dispersant

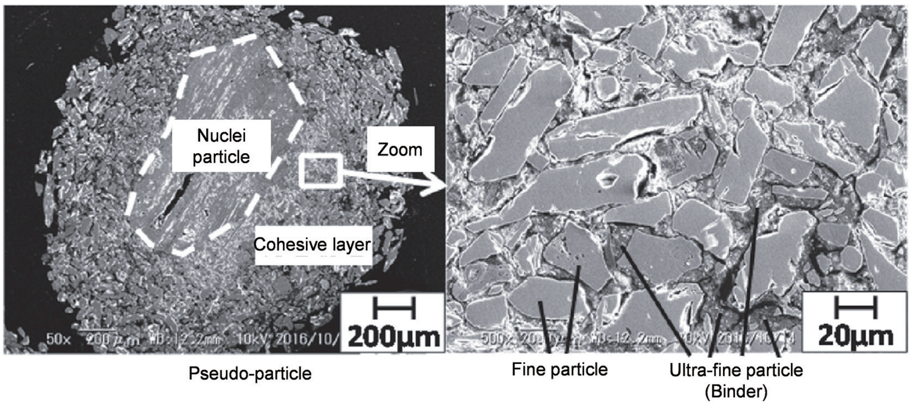

Fig. 10 Cohesive layer structure of pseudo-particle

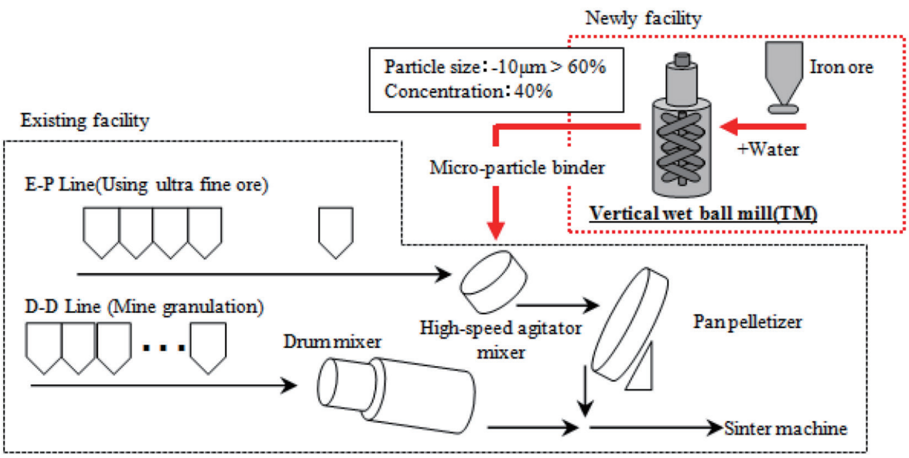

Fig. 11 Granulation process flow by using vertical wet ball mill

yield by binding primary hematite grains with high-strength bonds of calcium ferrite and improve the fluidity of molten liquid during the sintering process to enhance permeability in the fusion zone, and thus to improve sintering productivity. In addition, the coating of the pseudo grains with fine coke is designed to improve its combustion to enhance the reducibility of sintered ore through low-heat input sintering.

As stated above, many epoch-making ore agglomeration methods have been developed since 2000, and moreover, various technologies developed in the 1990s such as stand-support sintering and

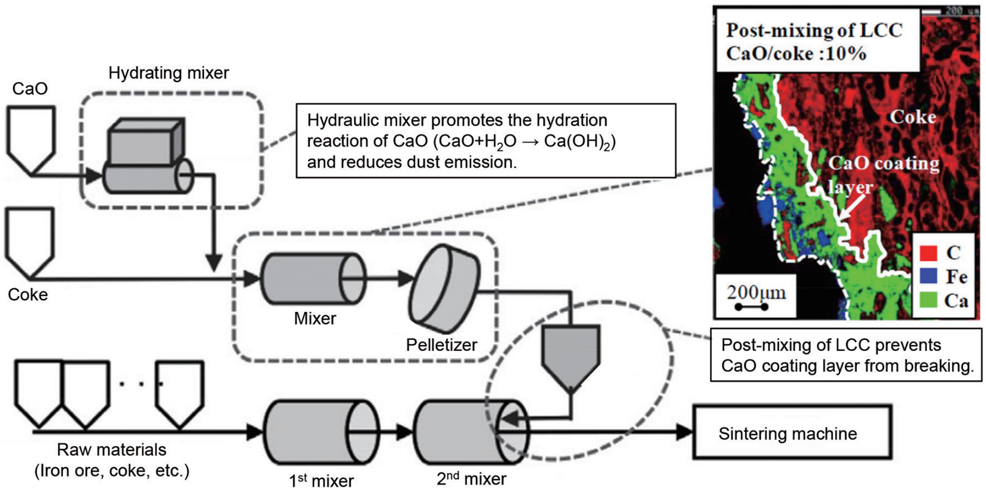

Fig. 12 Process flow of LCC

use of high-speed mixers were commercially introduced to many steel works during the same period. In parallel, spurred by the increasing demand in China for steel products, many steel works of Japan extended the length of sintering machines or expanded their widths. It became possible at the same time to increase the ore bed thickness thanks to practical application of various methods for permeability improvement, which allowed height increase of the side walls of sintering pallets. Sintering productivity has been greatly improved as a result of all these.

4.2 Environmental technologies

This sub-section relates to the technologies to cut the NO_x emission from sintering plants and those to lower the reducing agent ratio (to lower CO_2 emission) of blast furnaces by improving the reducibility of sintered ore.

Lowering NO_x emission is very important as an environmental measure of sintering plants. A popular method for decreasing NO_x emission is to treat it outside sintering machines using denitration facilities, but the equipment is expensive and its operation is costly. To solve the problem, the lime coating coke (LCC) process has been developed,[42, 43] whereby the NO_x source, fine coke, is modified so as to decrease the NO_x generation during its combustion in the sintering bed. As shown in **Fig. 12**, slaked lime ($Ca(OH)_2$), which is obtained through the hydration reaction of burnt lime, is mixed with fine coke and granulated into modified coke grains coated with the slaked lime, which are then mixed with fine ore as part of sinter feed. This process was commercially introduced at Nippon Steel's Oita Works in 2013, to achieve positive results of a 15% cut in NO_x emission, 1.1% rise of the sintering yield due to the fine coke agglomeration, and a productivity improvement of 0.6 t/day/m^2-grate area.

In addition to the above, hydrocarbon injection into the sintering bed has been commercially practiced.[26, 27] By this technology, hydrocarbon gas is blown to the sintering bed from above to supplement heat to the upper bed layer, where heating tends to be insufficient. This makes it possible to keep the ore bed in the temperature range of 1 200 to 1 400°C for a longer period without increasing the maximum temperature, have calcium ferrite, which is excellent in strength and reducibility, retained in the bed, and fine pores 1 μm or less in diameter remain while liquid-phase sintering is continued; all these make it possible to produce high-strength and high-reducibility sintered ore. In actual sintering operation, natural gas is used as the hydrocarbon gas, and a prescribed amount of it is blown to the air sucked from beneath the sintering bed under a hood above the sintering bed provided immediately behind the ignition furnace and covering a third of the machine length.

5. Developed and Commercially Applied Coke-making Technologies

5.1 Measures against change in coal quality and those for productivity enhancement

Japan is not blessed with the resources of coking coal, and a variety of coal pretreatment processes have been devised and commercially applied ahead of the rest of the world to increase the use of economical semi-soft coking coal;[44] such technologies include coal moisture control (CMC), the dry-cleaned and agglomerated precompaction system (DAPS), and the briquette-blend coking process (BBCP). Then, the development of a new coke-making equipment, named "the super coke oven for productivity and environment enhancement toward the 21st century (SCOPE21)," was launched as a national development project aiming at coping with the increasingly tight availability of coking coal (valuation of hard coking coal and the risk of resource depletion), enhancing coke-making productivity, protecting the environment, and saving energy. The research and development studies of the project began in 1994, and test operation was conducted from 2002 to 2003 using a pilot plant built at Nippon Steel's Nagoya Works.

A commercial coke oven was built in 2008 according to the SCOPE21 concept as No. 5 Coke Oven of Oita Works,[45, 46] and another in 2013 as No. 5 Coke Oven of Nagoya Works (see **Fig. 13**).[47, 48] SCOPE21 is regarded as the most significant success in the field

Fig. 13 Overview of Nagoya No. 5 SCOPE21 type coke oven battery

of coke-making in the last 20 years. By the process, coal is crushed, then simultaneously dried and classified into coarse and fine grains, rapidly heated to about 250°C, and then charged into coking chambers at that temperature (see **Fig. 14**). The process takes advantage of the modification of coal properties by rapid heating to 350 to 400°C, below the softening temperature of coal. This property modification results from the structural relaxation of coal due to the weakening of molecular interactions during rapid heating, and consequent increase in mobile components.[49] The developed technology makes it possible to increase the mixing ratio of semi-soft coking coal to 50%, far above the figure conventionally attainable, and the plant productivity by 1.7 times that of existing ovens, save energy equivalent to several tens of thousands of kilo-liters of crude oil per year, and cut CO_2 emission by 100 000 to 200 000 t/year.

5.2 Extension of coke oven life

The average age of coke ovens in Japan is as high as around 40 years at present. In this situation, oven operators are taking measures such as introducing SCOPE21 or other new coking processes, putting closed ovens back into operation, and padding up or replacing damaged bricks of existing ovens. Various oven life extension technologies are also being developed and actually applied. For oven life extension, systematic repair of coking chamber bricks based on early detection and quantitative damage diagnosis is essential, but conventionally chamber brick repair relied on visual damage inspection from outside, and based on that information, the repair work was mostly done manually. To solve the problem, the doctor of coke oven (DOC, see **Fig. 15**),[50] a machine for the diagnosis and repair of coking chamber walls in heat, has been developed; it was commercially introduced first to Nippon Steel's Oita Works in 2003.

Use of the DOC was expanded to the other works of the company,[3] and presently, the machine is capable not only of repairing lower chamber walls but also through holes at any part of the wall.[51] In addition, a technology has been established to calculate the wall surface waviness from images of the chamber wall, and based on them, estimate the force required for pushing coke out of the chambers.[52] Further, by applying structural analysis of discontinuous bodies, evaluation of the rigidity and strength of different types of brick structures of coke ovens has been enabled, as well as scientific clarification of the forming mechanisms of vertical cracks and through holes of chamber walls due to aging.[53]

Other coke oven life extension measures actually practiced in Japan include permanent chamber inside monitoring devices, chamber width measurement systems, hot refractory gunning machines for wall repair, and combustion chamber observation systems. These oven monitoring and repairing methods have actually been introduced significantly contributing to the extension of coke oven life against the advance of oven aging.

In the operation of aged coke ovens with damaged or roughened chamber walls, it is important to control the carbon deposits on coking chamber walls more studiously because carbon deposits affect the coke pushing load. Nippon Steel's Nagoya Works has introduced a carbon deposit control system to control the carbon burning time based on the O_2 concentration in the exhaust gas and thus control the coke pushing load (see **Fig. 16**).[54] By this technology, the CO_2 concentration (estimated from the O_2 concentration) in the exhaust gas is regarded as an indicator of carbon accumulation on the chamber walls, and the carbon burning time is controlled so that the CO_2 concentration falls within a prescribed range defined for adequate coke pushing load. Based on measurement of the changes in the chamber wall displacement and the gas pressure of operating chambers from coal charging to coke pushing, the wall displacement is largest at coal charging and it grows larger with increasing gas pressure.[55]

The fuel gas of No. 4 Coke Oven of Yawata Works, which was commissioned in 1965, was changed from the mixed gas of BF gas (BFG) and coke oven gas (COG) to pure COG during a temporary shutdown of the BF, and under this condition, the oven operation became unstable owing to condition change such as increased temperature difference between the upper and lower parts of the combustion chambers. This problem has been solved after facilities of dilute rich gas (DRG) were introduced to dilute COG with nitrogen.[56]

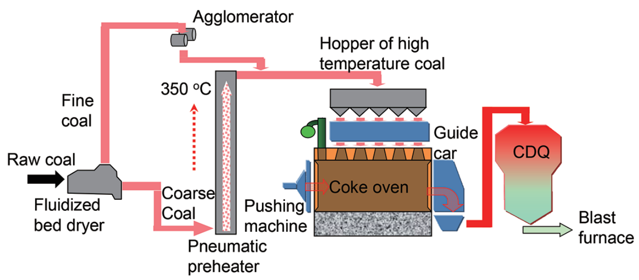

Fig. 14 Process flow of SCOPE21

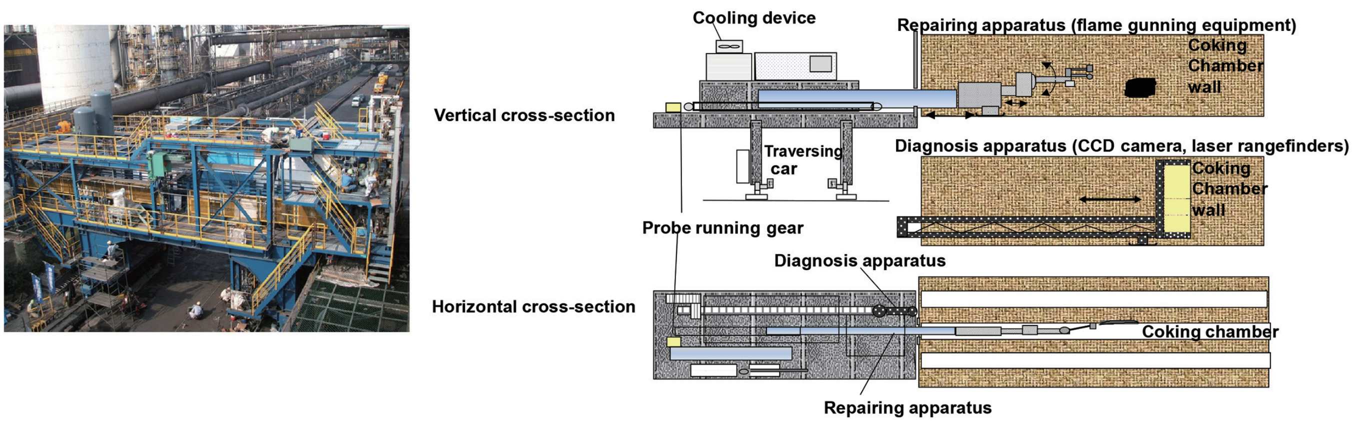

Fig. 15 Overview of doctor of coke oven (DOC) and schematic illustrations of its operation

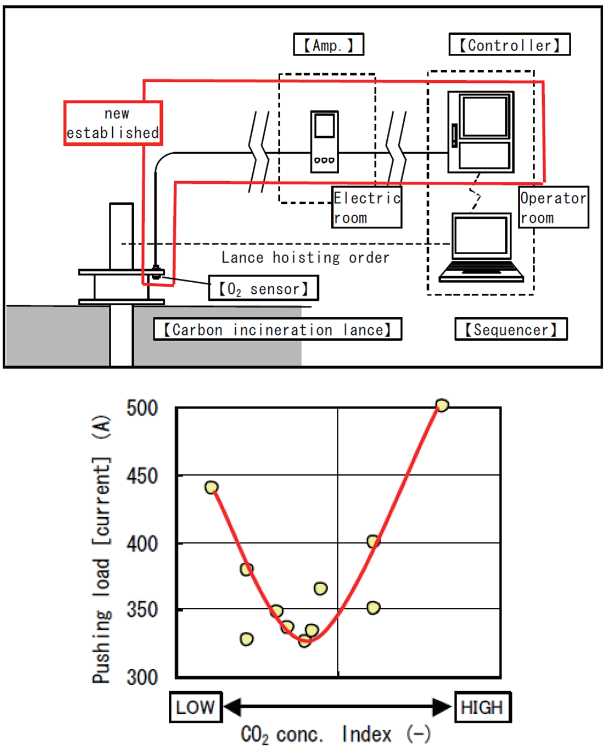

Fig. 16 Carbon deposit control system and relationship between CO_2 concentration in carbon burning exhaust gas and coke pushing load

6. Technologies of Material Recycling, Environment Conservation, CO_2 Emission, and New Fe Sources

6.1 Material recycling

The technology to use waste plastics as chemical raw material for coke ovens was put into commercial practice at Nippon Steel's Nagoya and Kimitsu Works in 2000,[57] and then expanded to other works. The cumulative amount of plastic waste from households for container and packaging uses recycled by Nippon Steel has surpassed 3 Mt,[58] significantly contributing to energy saving, decrease in CO_2 emission, and formation of a recycling-oriented society.

As a measure to further decrease the waste arising from steel works, rotary hearth furnaces (RHF) were installed at Nippon Steel's Kimitsu and Hirohata Works in 2000 to treat dust containing zinc in high amounts. Additional RHFs were built at Kimitsu, Hirohata, and Hikari Works to a total number of eight, and presently around 1 Mt of Zn-containing dust is converted every year into raw material for direct reduced iron (DRI), and charged into blast furnaces and electric arc furnaces,[59, 60] greatly saving resources and energy.

6.2 CO_2 emission

The Japanese steel industry has achieved the world's highest energy efficiency through continuous energy saving efforts,[61] and to respond to the need for further cutting CO_2 emission on a global basis, a national project for establishing revolutionary steelmaking processes to reduce CO_2 emission, the Process Technology Development for Environmental Harmony, has been launched.[62]

"The CO_2 ultimate reduction system by innovative technology for cool earth 50 (COURSE50)," an activity under the project, aims at developing the methods for increasing the hydrogen content in COG to partially replace coke for iron ore reduction and thus to decrease the CO_2 emission from the BF process by 10%, and by additionally applying separation and recovery of CO_2 from BFG, by roughly 30% in total (see **Fig. 17**).[63] Based on the fruits of the elementary technology development in Step 1 of Phase I in the fiscal years 2008 to 2012 (from April to March next year), a test blast furnace 12 m^3 in inner volume was built at Nippon Steel's Kimitsu Works, and combining the elementary technologies obtained, a series of overall pilot-level verification tests were carried out in Step 2 of Phase I in the fiscal years 2013 to 2017. The target 10% cut in CO_2 emission by reduction with hydrogen was confirmed possible, and the path to the target total cut in CO_2 emission including the CO_2 separation and recovery from BFG emerged. Step 1 of Phase II began in the fiscal year 2018, wherein tests to confirm the effective use of hydrogen are conducted on the test furnace.

Another activity of the project called "the process development for effective use of ferro-coke" is under way. Ferro-coke is a new type of formed and carbonized mixture of low-quality coal and iron ore, in which metal iron is dispersed in coke. The activity aims at lowering the reducing agent ratio by using the ferro-coke as a raw material for blast furnaces, anticipating that close packing of iron and carbon sources in the mixture is effective for such purpose. Under "the innovative process development to cope with changing availability of natural resources" in the fiscal years 2009 to 2012, a pilot plant to produce 30 t/day of ferro-coke was constructed,[64] and in a five-day test on No. 6 BF (5153 m^3 inner volume) of JFE Steel's East Japan Works Chiba in 2013, roughly 10% of coke was replaced with ferro-coke, and the reducing agent ratio was confirmed to actually decrease. In appreciation of this positive result, a five-year project was launched in 2017, under which a pilot plant to produce 300 t/day of ferro-coke is being built at JFE Steel's West Japan Works Fukuyama.

6.3 New iron sources

The development and commercial application of new ironmaking processes that may replace blast furnaces are steadily advancing in different countries.[65] The world production of reduced iron increased from approximately 0.8 Mt in the 1970s to 86 Mt in 2017 (while iron production by the BF route was 1180 Mt).[66] Direct reduction processes are divided into two types: those using natural gas as the reducing agent and those using coal. The Midrex and the Hyl processes, both using natural gas, are responsible for 60 and 15%, respectively of the world reduced iron production.[65] As a result of the shale gas revolution, economical shale gas has become widely available in North America, and the reduced iron production is expected to increase.

The RHF process described in sub-section 6.1 above is one of the processes using coal. Another called the ITmk3 process has been developed,[67] whereby iron pellets are produced by separating slag from the melted and reduced mixture of fine iron ore and coal fine; a first commercial plant having a capacity for 0.5 Mt/year was built in Minnesota, USA. FINEX is yet another process to reduce fine iron ore using coal to produce molten iron. Its first commercial plant is in operation, and a second one having a production capacity for 1.5 Mt/y (4300 t/day) was commissioned in 2007. The reducing agent ratio was 720 kg/t (510 kg/t coal briquette, 150 kg/t fine coal, and 60 kg/t coke) in 2008.

7. Conclusion

This article has provided an overview mainly of ironmaking technologies developed and commercially applied in Japan at and after the turn of the century. The first 20 years of the 21st century has been a period of revolutionary changes in the ironmaking field,

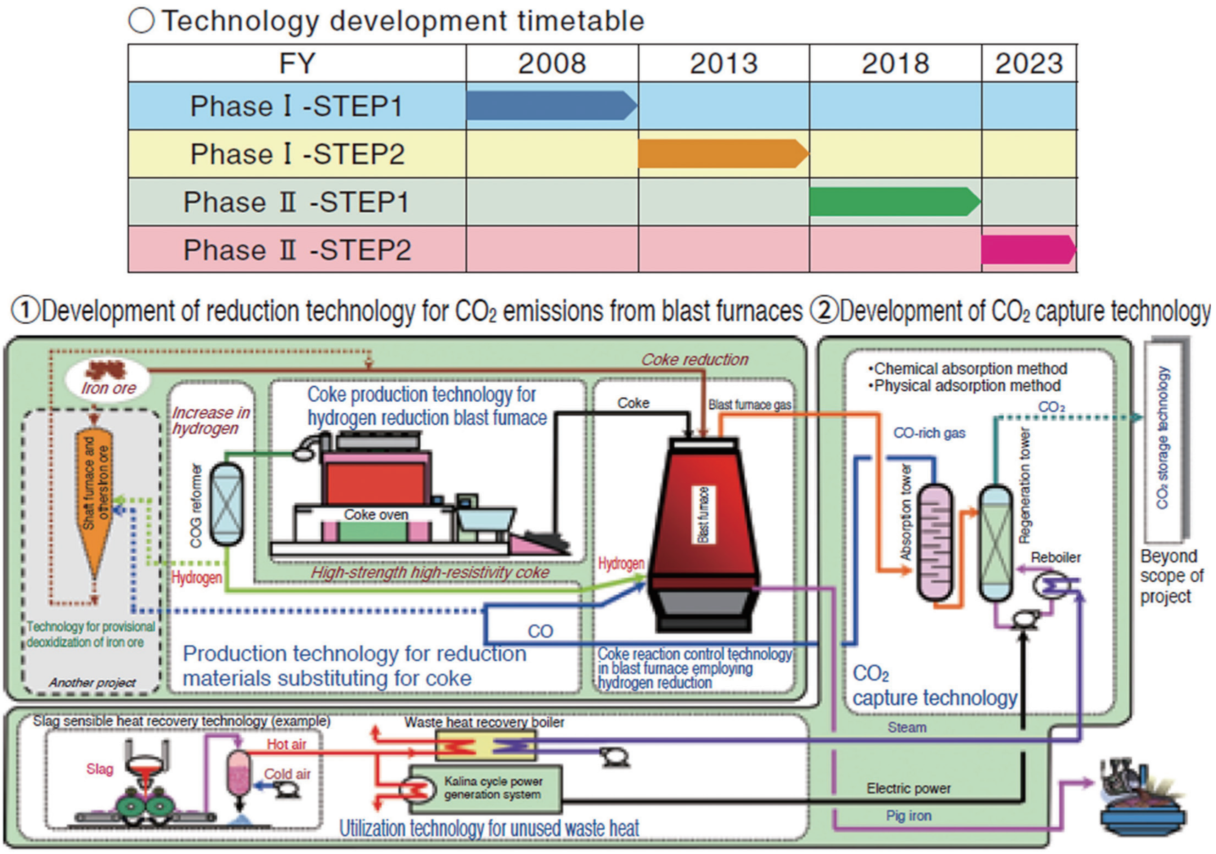

Fig. 17 Outline of the development of COURSE50 (CO_2 Ultimate Reduction System by innovative technology for cool Earth 50) project

but the conditions of this field of technology are expected to become tougher yet. For Japan's ironmaking to survive, it will be essential to maintain high-efficiency and stable operation against difficulties such as energy and environment problems, decrease in the workforce, aging of production facilities, increasingly tough competition in the world market, higher price, and lower quality of the raw materials. Development of new technologies breaking through past limits and actually applying them as presented in this edition will definitely open a new age of ironmaking.

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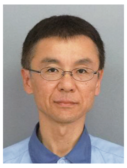

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