Recent Development of Ironmaking Technology in JFE Steel toward Carbon Neutrality

SATO Michitaka[*1] FUKADA Kiyoshi[*2] HASEGAWA Shinji[*3]

Abstract:

Since the last special issue on ironmaking (2008), the business environment surrounding the ironmaking field has dramatically changed. In other words, in addition to developing countermeasures to the soaring price of raw materials due to rise of China and deteriorating a raw materials grade, a countermeasure to the global warming becomes the most urgent issue since the Paris Agreement in 2015.

Against this background, this paper first summarizes the major technological developments; using technology of inexpensive and low grade resources and low RAR (reducing agent rate) technology at a blast furnace, that have been carried out in the fields of blast furnace, sintering, and coke-making of JFE Steel. Lastly, this paper will offer future prospects on the innovative technologies such as ferro coke and carbon recycling blast furnace that JFE steel is working on to realize the carbon neutrality in the future.

1. Introduction

Thirteen years have now passed since JFE Technical Report published its last Special Issue on Ironmaking[1)] in 2008, and the business environment surrounding the ironmaking field has changed dramatically during this period. Expressed in several keywords, the features of technological development in response to those changes can be summarized as (1) response to sharp price increases and deterioration of the quality of raw materials, (2) response to global warming and carbon neutrality and (3) use of digitalization and data science technology.

As an overview of the topics covered in this Special Issue, this paper first summarizes the changes in the environment surrounding the ironmaking field during the past approximately 10 years, and then introduces the technological developments carried out in the ironmaking field at JFE Steel in response to the above-mentioned keywords (technical systems). Due to space limitations, this paper will focus on technologies related to (1) and (2). The reader is invited to refer to the individual papers in this Special Issue for details concerning technological development related to (1) and (2), and to the previous Special Issue on Data Science[2)] for technologies related to (3).

2. Changes in the Business Environment Surrounding the Ironmaking Field

Figure 1 shows the trend of crude steel production in the world and in Japan[3)]. Since 2000, Japan's crude steel production has remained slightly less than 100 million ton/year. On the other hand, the BRICs countries have enjoyed remarkable economic growth, and in particular, China's crude steel production exceeded the major 1 billion-ton mark for the first time in 2020. Due to these increases in steel demand, the prices of iron ore and coal increased sharply after 2000 and remain at high levels even now (**Fig. 2**) [4, 5)]. At the same time, the quality of raw materials is gradually deteriorating, and the development of technologies that make skillful use of these low grade resources is strongly demanded.

The trend in the average reducing agent rate (RAR)

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*1 Dr. Eng.,
Principal Researcher,
Steel Res. Lab.,
JFE Steel

*2 Dr. Eng.,
Executive Assistant,
General Manager,
Ironmaking Research Dept.,
Steel Res. Lab.,
JFE Steel

*3 Executive Assistant,
General Manager,
Ironmaking Technology Dept.,
JFE Steel

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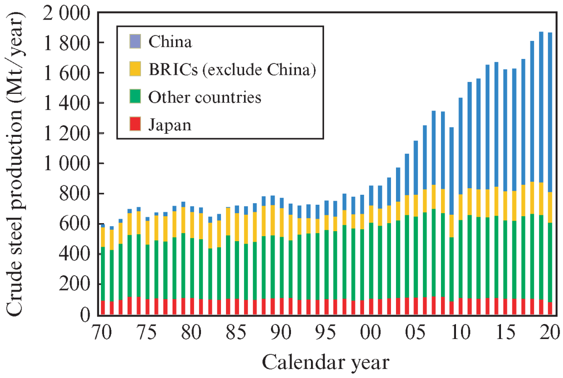

Fig. 1 Trend of crude steel production in the world

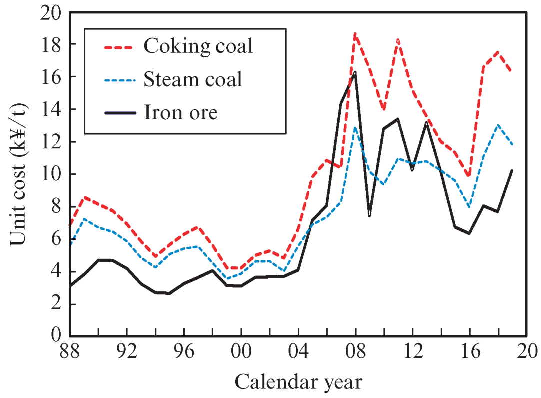

Fig. 2 Trend of raw materials unit cost in Japan

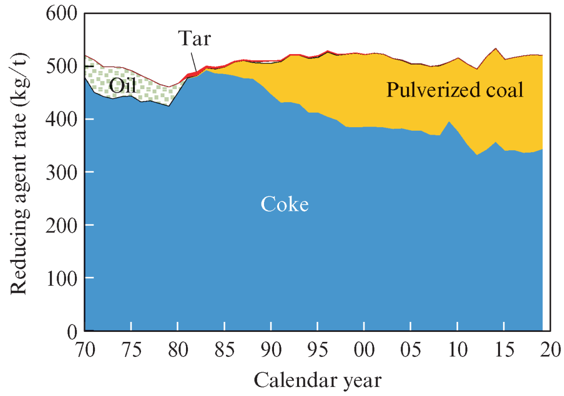

Fig. 3 Trend of reducing agent rate in Japan

at all blast furnaces in Japan and the breakdown by type of reducing agent are shown in **Fig. 3**[6]. After 1980, there was an orientation toward high pulverized coal injection rates (PCR) in blast furnace operation, in which comparatively cheap pulverized coal was used in place of expensive coke, but since 2000, there has been a continuing shift to technological development aimed at reducing RAR in response to growing calls for CO_2 reduction in the iron and steel industry as a whole. However, RAR has shown a flat trend at around 500 to 520 kg/t in recent years, as is clear from Fig. 3, suggesting the inevitable conclusion that RAR reduction has essentially reached its technical limit. Thus, innovation which is not simply an extension of existing technologies will be essential in order to achieve further reductions in RAR.

From the beginning of the 2010s, prevention of global warming has been positioned as an urgent issue in both Japan and other countries. In 2015, the Paris Agreement was adopted with aim of holding global temperature rise to no more than 2°C, and in the years that followed, achieving carbon neutrality has become a global trend. In Japan as well, the government worked out various policies and plans in rapid succession, and on October 26, 2020, then-Prime Minister Yoshihide Suga announced Japan's 2050 Carbon Neutral Declaration. In advance of this, the Japan Iron and Steel Federation (JISF) announced the "Long-term vision for climate change mitigation: A challenge towards zero carbon steel" in November 2018. In addition to the three ecos + innovative technologies (COURSE50 and ferro coke technology; described in Chapter 4 below), the steel industry also intends to develop super innovative technologies, including hydrogen reduction ironmaking and CCU (Carbon Capture and Utilization) by 2100[7]. In light of these rapid developments in Japan and overseas, in February 2021, the JISF announced the "Basic Policy of the Japan steel industry on 2050 Carbon Neutrality aimed by the Japanese government" and declared that the Japanese steel industry will "aggressively take on the challenge to achieve zero-carbon steel" in 2050[8]. Based on these moves, JFE Holdings also announced the JFE Group Environmental Vision for 2050, which lays out an ambitious vision of achieving carbon neutrality in 2050 and presented a roadmap for achieving that goal[9].

In the midst of these rapid changes in the business environment, Chapter 3 presents an overview of the technologies developed or applied in practical operation by JFE Steel in approximately the past 10 years in the blast furnace, sintering and coke making fields, and Chapter 4 describes the prospects for the development of innovative technologies by JFE Steel envisioning the achievement of carbon neutrality.

3. Overview of Technological Development in Ironmaking Processes

3.1 Blast Furnace Process

Table 1 summarizes examples of research and development in the blast furnace field in approximately the recent 10 years.

To improve the gas utilization efficiency of top gas for low RAR operation, a high ratio coke mixed charging technology of mixed charging of massive

Table 1 Research and developments in blast furnace process

Process	Technology
Fundamentals	Solid flow, segregation and mixing behavior analysis model with DEM
Burden charging	High ratio coke mixed charging & FCG dynamic control
	Small coke mixed charging by segregation control in bunker
	Development of cohesive layer simulator
Tuyere injection	High PC injection supported by sophisticated mathematical simulation
	PC and LNG co-injection
Measurement	On-line coke fine measurement system
Data science	Blast furnace operation guidance system (Heat level in lower part, pig iron temperature, permeability)

coke into the ore layer was applied in commercial operation in 2006 at East Japan Works (Chiba District) No. 6 blast furnace[10] (hereinafter, Chiba 6BF; similar notations will also be used for other facilities). This technology utilizes multi-batch charging by the bell-less type charging system with three parallel top bunkers (3PB) and an ore and coke simultaneous discharging, which is an original technology developed by JFE Steel. The company also developed the FCG (Flow Control Gate) dynamic control method, which is contributing to reduction of RAR[11]. On the other hand, to reduce RAR by appropriate use of small coke without depending on equipment such as 3PB or the center feed-type bell-less top bunker, JFE Steel also developed a burden distribution control method which enables precise control of segregation behavior in bunkers[12]. A new cohesive zone simulator was also developed to experimentally clarify how the mixing condition at the upper shaft of blast furnace affects reducibility and permeability in the cohesive zone[13] and is contributing to understanding the phenomena in the lower part of the blast furnace. Great progress has been achieved in numerical analysis of mixed charging, and a technology that enables simultaneous and detailed analysis of the charging and segregation behaviors of individual particles in the blast furnace and the reaction behavior between particles was developed using DEM (Discrete Element Method)[14].

In the area of tuyere injection technology, there is the orientation toward massive coal injection at all blast furnaces, and JFE Steel has positioned the eccentric double lance as a high-combustibility lance in actual operation[1]. In recent years, substantial progress has been made in numerical analysis techniques which contribute to understanding combustion behavior, as seen in the proposal of a mathematical model for advanced pulverized coal combustion[15], which is based on LES (Large Eddy Simulation) model and extended CPD (Chemical Percolation Devolatilization) model. On the other hand, at East Japan Works, a natural gas and pulverized coal (PC) co-injection technology was developed focusing on natural gas as a hydrogenous reducing agent (HRA), and has demonstrated its effectiveness in increasing productivity and reducing CO_2[1]. To further increase the pulverized coal injection rate (PCR) and reduce CO_2 emissions, the proper arrangement of the natural gas and PC injection lances and a double-channel lance for natural gas and PC were also proposed, and their effects have been verified by tests with an experimental furnace (hot model) and numerical analysis[16].

Concerning to measurement technology for the blast furnace, advances have been achieved in real-time measurement technologies. A technology that enables online measurement technique of ratio of coke fines on the belt conveyor was applied practically by utilizing brightness analysis (normalized image brightness) of camera images[17], and has been extremely useful for understanding the properties of burden materials. Rapid progress is also being made in application of CPS (Cyber Physical System), which performs modeling of various types of blast furnace probe information (Physical) onto virtual Cyber space, and a system that provides guidance on the furnace heat and hot metal temperature and permeability was implemented[17]. In the future, development of CPS as a tool for further achieving automated operation is expected.

Figure 4 shows the trends of the blast furnace inner volume, together with PCR as a representative parameter of blast furnace operation expressed as relative values against the average value for 2003. Total inner volume is roughly constant at around 40 000 m^3, and since

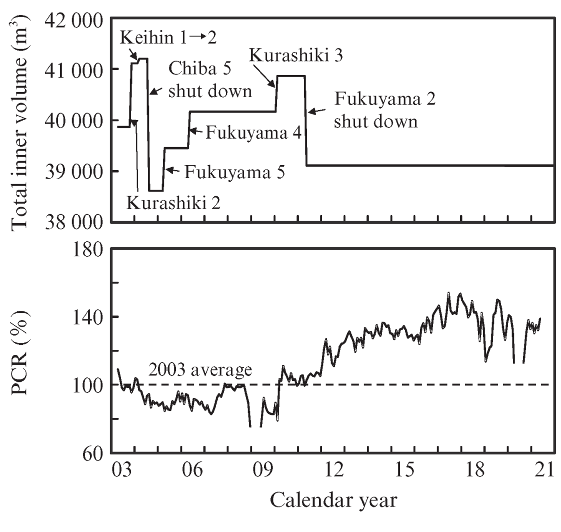

Fig. 4 Trend of inner volume of blast furnace and PCR

2010, PCR has gradually increased as facility was reinforced. Due to the effects of the coronavirus crisis, there were some variations during the period from 2019 to 2020, as West Japan Works Fukuyama 4BF was temporarily banked and West Japan Works Kurashiki 4BF was blown out for furnace relining. However, in spite of those changes, it can be understood that the pulverized coal injection rate has been increased by approximately 50 % during the past 10 years.

3.2 Sintering Process

As raw materials for sintering, there has been a shift from South American ore to Australian ore from the viewpoint of reducing transportation costs, and at the same time, among Australian ores, deterioration of iron ore quality due to an increase in iron ore with a high content of combined water and an increase in gangue components (particularly SiO_2 and Al_2O_3) accompanying the depletion of high grade hematite ore. These changes in the raw materials for sintering invite decreased productivity of sintering machines and an increased bonding agent ratio, while also causing the problem of reducing strength. **Table 2** summarizes examples of research and development in the sintering process to address these issues during approximately the last 10 years.

In mixing and granulation technology, the coke breeze and limestone coating granulation technology was developed in the first half of the 2000s, and because improvements in productivity and the reducibility index (RI) were demonstrated, this technology had been expanded to 6 of JFE Steel's 7 sintering machines by 2011[18].

Table 2 Research and developments in sintering process

Process	Technology
Fundamentals	Intra-particle water migration dynamics
	Dephosphorization technique
Granulation process	Limestone and coke breeze coating granulation
	Agitating, mixing and granulation model
New agglomerate	Carbon core pellet
	Return fine agglomerate
Carbonaceous bonding agent reduction	Sintering with combined usage of coke breeze and gaseous fuel (Super-SINTER™)
	Super-SINTER™ with oxygen enrichment
	Utilizing oxidation heat of magnetite ore
	Biomass usage as bonding agent
Sinter quality	RDI reduction
Sintering machine	Two-stage combustion burner at ignition furnace
	Pallet length extension (Keihin 2 sintering machine)
	Restart operation (Fukuyama 3 sintering machine)

As a new agglomerate that fundamentally improves sinter quality, a new double layer pellet production technology was developed. In this method, green pellets with a double layer structure are obtained by coating a carbon core particle with fine ore with a disc pelletizer. When this carbon core green pellet is sintered in the sintering machine, a carbon core pellet is obtained, and it has been confirmed that the RI value of this new agglomerate is remarkably higher than that of conventional sinter[19].

Natural gas injection in the sintering machine (Super-SINTER™) is a revolutionary new production process that expands the suitable temperature range of 1 200 to 1 400°C for formation of a high strength, high reactivity calcium ferrite phase by injection of a small amount of natural gas above the sinter bed. This technology was applied to an actual machine at East Japan Works Keihin No. 1 sintering machine (Keihin 1SM) in 2009 for the first time in the world, and improvement of sinter quality (TI: tumbler index, RDI: reduction degradation index) and reduced consumption of bonding agents was verified. Since it is only necessary to add comparatively small-scale equipment (i.e., a natural gas injection hood), this technology has been applied at all 7 of JFE Steel's sintering machines[20]. In addition, a technology which improves productivity by simultaneous injection of natural gas and oxygen was also applied to an actual machine at Chiba 4SM[21]. As a result of the development of these technologies, the RDI at JFE Steel has decreased continuously (**Fig. 5**), contributing to high PCR, low RAR operation.

On the other hand, considering recent calls for CO_2 reduction, reduction of the use of carbonaceous bonding agents such as coke breeze and anthracite has become an important issue. As one countermeasure, a technique for reducing bonding agent consumption by using magnetite ore as a raw material and utilizing its

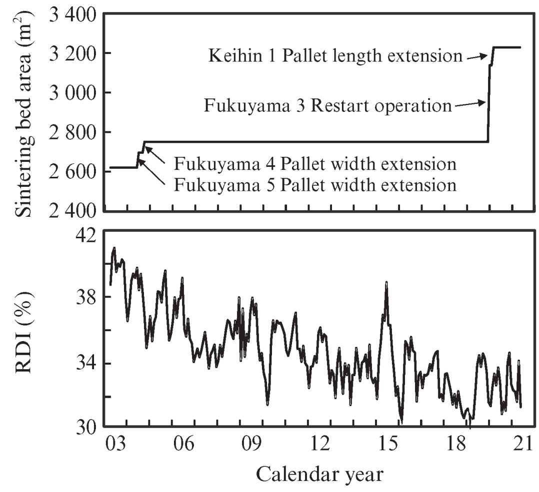

Fig. 5 Trend of sintering bed surface area and RDI

oxidation heat has been studied[22]. By using magnetite in combination with the magnetic dispersing feeder, which is a JFE Steel original technology, it is possible to control segregation during feeding. As a completely different approach, a process using carbon-neutral biomass is also being studied as part of joint research through an industry-academic partnership, aiming at practical application[23].

As part of efforts to strengthen the basic technology of the sintering process, a much deeper understanding of granulation and mixing phenomena has been achieved. Basic research is being carried out on a continuing basis, anticipating progressive deterioration of ore quality in the future (increase in ores with high combined water content, increase in gangue components, ore fines. Achievements in this connection include evaluation of the relationship between iron ore properties and intra-particle water migration dynamics during iron ore granulation[24] and elucidation of the influence of agitation conditions on the mixing and granulation process[25]. Because an increase in phosphorus (P) content in ore is assumed in the future, JFE Steel is also participating in the development of a dephosphorization technique as an all-Japan effort in a National Project[26].

As means of fundamentally increasing sinter production capacity, Fukuyama 3SM was restarted in December 2019 and the length of Keihin 1SM was extended in March 2020, resulting in an increase of approximately 17 % in the sintering bed surface area, as shown in Fig. 5. In addition, in 2015, a two-stage combustion burner for the sintering machine ignition furnace was developed and installed at Kurashiki 2SM, achieving an energy saving of approximately 30 %[27]. This technology is being transferred to other plants company-wide, as a large CO_2 reduction effect can be expected.

3.3 Coke Making Process

Due to the sharp rise in the price of coking coal since 2000 as shown in Fig. 2, reducing the use of caking coal and increasing the blending ratio of low grade coal such as non- or slightly-caking coal in the coke making process became an urgent issue, and from the blast furnace side, there was also heightened demand for increased coke strength as a technology for realizing increases in PCR. In addition, since the 2000s, deterioration with age and declining productivity emerged as problems with all coke ovens constructed during the era of high economic growth in Japan in the 1970s. Against this background, JFE Steel systematically promoted renovations (pad-up renewal) of aged coke ovens[28], while also developing technologies capable of satisfying both use of inexpensive low grade coal and improvement of coke strength, as well as diagnosis and repair techniques for aged ovens (**Table 3**).

Table 3 Research and developments in coke making process

Process	Technology
Fundamentals	Coal surface characterization by Raman spectroscopy
	Coke particle breakage model by DEM
Novel measurement method for coal	Permeation distance as new index
	Surface tension of coal and semi-coke
Coal pretreatment	Addition of aromatic amines
Coal blending	Advanced blending based on permeation distance and surface tension of coal
Coke discharging from coke ovens	Deformation of damaged coke oven wall by DEM model
	Coke cake discharging behavior based on clearance model
Life prolongation of coke ovens	Monitoring refractory wear
	Hot repair technique of coke oven brick work
Data science	Operation guidance system to reduce pushing load of coke ovens
	Decentralized adaptive control of coke oven batteries

New approaches to coal evaluation methods were also proposed, and these were used as coal blending guidelines for the production of high strength coke. Two representative examples are permeation distance and surface tension of semi-coke, which enable quantitative evaluation of the properties of interaction and compatibility between different coals [29, 30]. Coal surface characterization by Raman spectroscopy is also positioned as a new evaluation technique[31]. A technique for direct coal upgrading by addition of aromatic amines was proposed[32], and is expected to contribute to coke strength improvement. As a numerical analysis technique for coke strength, a technique based on the Discrete Element Method (DEM) was developed[33]. This technique has attracted attention not only for evaluation of coke breakage behavior in the blast furnace, but also for evaluation of variations in coke strength.

As operational technologies for aged coke ovens, JFE Steel developed simulation models for oven wall deformation during pushing[34] and coke cake discharging behavior (push-ability)[35] which have contributed to a deeper understanding of pushing behavior. At the same time, the company has also made efforts to maintain stable operation and prolong the service life of aged coke ovens through linkage with coke oven wall damage monitoring and a new measurement method for the bulge shape using the Laser-Scanner (LS

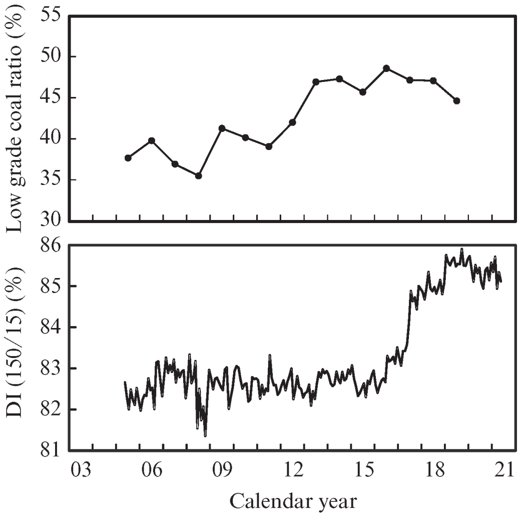

Fig. 6 Trend of low grade coal ratio and drum index (DI)

method)[36]. Recently, an operation guidance system to reduce the pushing load of coke ovens[37] and decentralized adaptive control of coke oven batteries[38] utilizing data science have been developed and applied, and are making important contributions to stable operation.

Figure 6 shows the trend of Japan's national average low grade coal use ratio[6] and the drum index (DI (150/15)) at JFE Steel during the same years. Although the low grade coal ratio is a national average, its trend at JFE Steel seems to follow a generally similar pattern. As these graphs suggest, although the low grade coal ratio has continued to rise gradually since 2005, improvement of DI was achieved as a result of the research and development described above. Moreover, it appears that this improvement in DI has also made a significant contribution to the increase in PCR shown in Fig. 4.

4. Development of Innovative Processes for Achieving Carbon Neutrality

This chapter focuses on ferro coke and COURSE50 as innovative processes being developed as National Projects, and presents an outline of the status of development. The features of the oxygen blast furnace process, which is being developed independently by JFE Steel as a future technology, are also described, together with the concept of the carbon recycling blast furnace based on the oxygen blast furnace as a further evolution of that technology.

4.1 Ferro Coke

Ferro coke is a composite that consists mainly of coke while also containing about 30 % metallic iron, and is an innovative blast furnace raw material which has remarkably high reactivity with CO_2 gas due to the catalytic effect of the metallic iron. In principle, a substantial reduction in the RAR of blast furnaces is expected to be possible by lowering the thermal reserve zone temperature in the blast furnace. The initial work on ferro coke was carried out between 2009 and 2012 in the project "Technological Development of Innovative Ironmaking Process to Enhance Resource Flexibility" with financial support by Japan's New Energy and Industrial Technology Development Organization (NEDO). As part of that effort, a 30 t/d scale pilot plant was constructed at JFE Steel's East Japan Works (Keihin District). Development of the ferro coke production technology was demonstrated with a capacity of 30 t/d, and the effect of RAR reduction effect of ferro coke in an actual large-scale blast furnace was verified in a 5-day test[39].

Following this, from FY 2017, development is being carried out to verify the effects of mass-production technology with a medium-scale facility 10 times larger than the above-mentioned pilot plant (300 t/d) and long-term continuous use of ferro coke in the blast furnace with financial support by NEDO over a scheduled period of 6 years in the project "Technological development of ironmaking process utilizing ferro coke." At present, the medium-scale facility is installed at JFE Steel's West Japan Works (Fukuyama District), where test operation began in October 2020. After demonstrating the production technology using this facility, establishment of a technology with the goal of reducing energy consumption in the ironmaking process by approximately 10 % by around 2023 is targeted (including simulations)[39].

4.2 COURSE50

COURSE50 (CO_2 Ultimate Reduction System for Cool Earth 50) is a National Project targeting approximately 30 % mitigation of CO_2 emissions from an integrated steel works which is to be achieved by (1) Substitution of hydrogen for some coke used as a reducing agent in the blast furnace process (10 % CO_2 reduction) and (2) separation and capture of CO_2 generated from the blast furnace (20 % CO_2 reduction). This project was commissioned by NEDO and started in July 2008 as a 5-year fundamental R&D project (Phase I STEP 1), Development of fundamental technologies, followed by a 5-year integrated R&D project (Phase I STEP 2) that includes iron ore reduction by hydrogen and CO_2 separation, capture and recovery as Integrated development of CO_2 reduction technologies. The project is currently in the practical development stage (Phase II STEP 1)[39].

JFE Steel is responsible for study of the combustion behavior of pulverized coal and hydrogen-containing reductant gas such as COG (coke oven gas) in the raceway, development of a technology for suppressing reduction degradation of sinter by utilizing hot top gas injection from the upper shaft tuyeres (preheating gas injection), development of a CO_2 separation and capture technology by physical adsorption technology, etc., thereby contributing to the establishment of the COURSE50 process. In the future, this project is scheduled to transition to Super COURSE50 utilizing H_2 from outside (carbon-free H_2)[7], and a concept for carrying out this development using NEDO's Green Innovative Fund (GI Fund) has been presented[40].

4.3 Carbon Recycling Blast Furnace Based on the Oxygen Blast Furnace

In the 1980s and 1990s, various oxygen blast furnace processes were proposed, in which cold oxygen (room temperature, oxygen concentration: 100 %) was blown from the tuyeres in place of hot blast (oxygen concentration: approx. 21 to 27 %). As an N_2-free process, the oxygen blast furnace has the intrinsic feature of accelerating the ore reduction rate, but gas injection at the upper or lower shaft is an essential process because heating-up of the burden is insufficient due to a decrease in the gas volume in the shaft accompanying the lower gas flow rate. From the 2000s, the oxygen blast furnace process was reviewed from the viewpoint of CO_2 reduction, and JFE Steel's advanced oxygen blast furnace[41] and others were proposed. Because one feature of the JFE advanced oxygen blast furnace is massive injection of a hydrogen-containing reductant gas (natural gas), the target of this development is CO_2 reduction by increasing hydrogen reduction.

Because the blast furnace gas (BFG) from this oxygen blast furnace process does not contain N_2, CO_2 separation and coupling with CCU are easy. Therefore, JFE Steel proposed a so-called carbon recycling blast furnace[9], in which methane is synthesized by using captured CO_2 from the blast furnace and H_2 from outside (carbon-free H_2) according to the methanation reaction ($CO_2 + 4H_2 = CH_4 + 2H_2O$), and the carbon in the synthesized methane is then reused in the blast furnace. In other words, the CO_2 from the blast furnace is converted into a carbon-neutral reductant (methane) by using hydrogen, and this methane is recycled repeatedly, replacing conventional coal-based reductants. Because this process enables massive recycling of methane, which is considered to be C-free, a reduction of approximately 30 % in CO_2 generated by the blast furnace can be expected in comparison with the conventional blast furnace process. A development concept using the above-mentioned NEDO Green Innovation Fund has also been proposed for this process[40], which is expected to contribute to realizing carbon neutrality in the future.

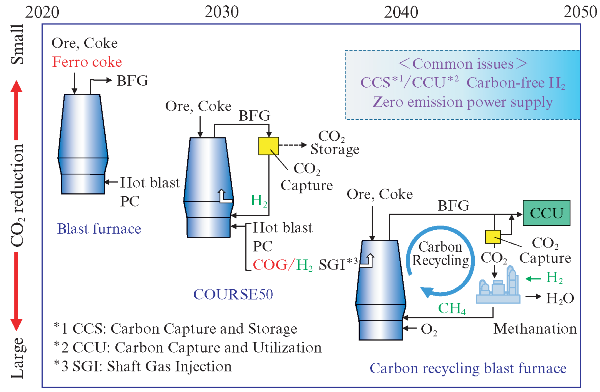

Fig. 7 Way to carbon neutral ironmaking technology

5. Conclusion

Since the previous Special Issue on Ironmaking in 2008, the business environment surrounding the ironmaking field has seen a series of profound developments, including the remarkable emergence of Chinese mills, growing calls for prevention of global warming at the worldwide scale, and resulting moves to realize carbon neutrality in the steel industry, and today the steel industry is in the midst of sudden changes with no historical precedent.

In that environment, in the future, JFE Steel will work to improve sinter and coke quality premised on the use of low grade raw materials by combining its total capabilities in all fields, and will pursue rationalization and CO_2 reduction technologies through reduction of the RAR of blast furnaces. To realize a radical reduction in CO_2 in the future, we will continue to take on the challenge of steady development and practical application of ferro coke technology, COURSE50 and the carbon recycling blast furnace, as shown in **Fig. 7**, and will work diligently toward the realization of carbon-neutral steel.

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