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Future of Ironmaking: Review

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Abstract

Ironmaking is considered an energy-intensive sector as it requires huge natural resources. The iron and steel industry is vital for the economy worldwide. It could be regarded as the main backbone of many industries as construction, transportation, and manufacturing. Technically, the iron & steel industry was developed in the last years resulting in significant revaluation in the main parameters controlling the whole industry. Ironmaking generally takes three main techniques: blast furnace, direct reduction, and smelting. Many controlling parameters are strongly affecting the technological changes in ironmaking, which must be considered when handling any new trend and/or deciding on the best technique that could be selected for further investment in ironmaking. Energy consumption is the main deriving force, besides other factors such as environmental impact and operational costs. The present review will handle the current status and future of ironmaking. The environment which is prompting the enhancement of ironmaking will be clarified. The article introduces the process developments and quality of the main routes of the ironmaking industry. The future ideas for developing ironmaking processes will be described as well.

Keywords: Ironmaking; Blast furnace; Direct reduction; Smelting; Iron ores

1. Introduction

Ironmaking processes consume immense energy and emit significant amounts of greenhouse gas [1], with more than 2 billion tonnes of CO_2 emitted annually. Iron & steel makers considered four essential routes to produce steel [2]; three are mainly based on reducing iron ores in blast furnaces, direct reduction, and direct smelting. The last technique includes melting steel scrap directly in electric arc furnaces. Both blast furnace and smelting reduction processes use coal-based reductants to produce molten metal, separating gangue materials as slag. The direct reduction processes plants mainly depend on using gaseous hydrogen-rich sources as reductants or, in some processes, coal as a reductant to reduce iron ores to sponge iron (Direct Reduced Iron, DRI, or Hot Briquetted Iron, HBI). However, the hot metal produced in blast furnaces and smelting plants is refined to crude steel in primary oxygen converters. Direct reduction plants' solid DRI/HBI is converted to liquid steel using arc furnaces. To date, the conventional blast furnace technology is considered the principle mean of hot metal production, although there is a significant revolution to develop new ironmaking technologies with high–intensity production of iron at a relatively lower cost, based mainly on direct and smelting reduction processes. All these new ironmaking processes aim to eliminate or reduce the energy supply by coke and/or coal [3]. However, most current data revealed that coal should form the basis of all the alternative ironmaking processes. On the other hand, the operation of blast furnace process is always associated with many complicated problems in terms of using vast amounts of expensive metallurgical coke and other raw materials supporting facilities in the sintering plant and gas cleaning system. All these factors make the classical blast furnace highly capital-intensive cost. However, towards minimizing the energy consumption and operation costs of ironmaking processes, significant improvements of the alternative technologies should continue to achieve the best performance in energy consumption and greenhouse gas emission reduction.

2. Ironmaking processes

2.1. Blast furnace technology

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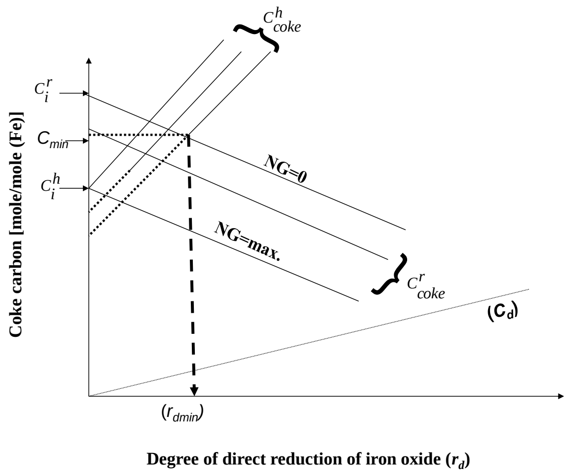

Fig.1 The relation between amount of coke carbon and degree of direct reduction [6-7]

$$(\Delta C_{max} = C_{min} - C_i^h)$$

A blast furnace (BF) is an cheapest-efficient plant in ironmaking. The primary source of energy in BF technology is metallurgical coke. The coke consumption in BF determines to a great extent, the cost of hot metal production. As mentioned in literature [4] by Peacey- Devenport, coke costs about 55% of the total cost of pig iron production. Today, blast furnaces operators are focusing on finding new energy sources or developing alternative substitutions to replace the carbon of coke. The application of natural gas and/or pulverized coal injections greatly minimized coke consumption in modern iron blast furnaces. The blast furnace is still a competitive technology because of several innovative developments in many sectors related to the design aspects of the blast furnace equipment. For example, the production rates of modern blast furnaces become more than 12,000 ton per day, and the fuel rates become around 450 kg/thm (In some companies, 275 kg coke and 175 kg coal). Also, the BF efficiency or availability ranging 95-88% as a result of improved operation parameters and other factors associated with BF performance. Molten metal is produced with very low silicon (about 0.2%). The campaign life of modern BF is more than 15 years. Innovations in measuring tools as well as the use of mathematical models, have been radically improved the method of monitoring the blast furnace operation. Lower energy consumption and higher productivity achievable with increased oxygen enrichment and extensive coal injection is today realistic expectations. Expert systems - intelligent computer programs also can play a role in solving complicated problems of blast furnace operation.

One of the standard techniques used in modern blast furnaces is composite blast technology in which natural gas and coal are injected by tuyeres directly to the hearth of the furnace. The technology was invented at Dnepropetrovsk Steel company in 1957, Ukraine. It's well known that natural gas is composed of methane (90-99% CH_4), when injected with air blast into the oxidized zone of the furnace, CH_4 is oxidized by oxygen to form carbon monoxide and hydrogen ($CO+H_2$). The free hydrogen is a strong reducing agent and therefore, the degree of direct reduction of iron oxide (r_d) will be decreased. Such a decrease in direct reduction percentage is considered an important source for saving coke in iron blast furnace.

The above mechanism was demonstrated by Pavalov [5], he demonstrated that both direct and indirect reduction reactions inside BF are different not only in heat consumption but also in the amount of reductant as shown in the following Equations:
(where k_1 = equilibrium constant, and ΔH = enthalpy of the reaction).

$$FeO + (\frac{1}{k_1} + 1)CO = Fe + CO_2 + (\frac{1}{k_1})CO \qquad \Delta H_{T1} = -13.1 \ kJ/mol.Fe \qquad (1)$$

$$FeO + C = Fe + CO \qquad \Delta H_{T2} = 15.4 \ kJ/mol.Fe \qquad (2)$$

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It is clear that $\Delta H^0_{T1} \succ\succ \Delta H^0_{T2}$ but $(\frac{1}{k_1}+1)$ always greater than the unit.

It's interesting to confirm that direct reduction needs less amount of reducing agents than indirect reduction (according to Pavalov at T=958 K; k_1=0.72 and (1/k_1+1) = 2.39 >1).

Based on these calculations, the degree of direct reduction is considered the most important index in the operation of BF with composite blast technology. The natural gas can be mixed with air blast till reaching the minimum value of direct reduction. In another literature [6-7], Andronov demonstrated that natural gas injection by tuyeres is useless at a direct reduction (rd) less than 0.10-0.15. The injection of natural gas enriched with oxygen into BF increases the chance of lowering the immediate reduction percentage to a minimum value with conditions keeping other parameters in acceptable indices.

The development of advanced mathematical models enables blast furnace operators to control and improve the operation parameters of a blast furnace. In related investigations, the author of the present work developed mathematical models and designed a roadmap to optimize the operation parameters of iron blast furnaces [8-12].

The minimum value of direct reduction can be derived from PDK model [6] as given in Equation (3);

$$r_{d_{\min}} = \frac{\frac{1}{\bar{\eta}_{CO}} - n\left[2\frac{\bar{\eta}_{H_2}}{\bar{\eta}_{CO}} - \frac{Q_{CH_4}}{Q_{C_t}} + 1\right] - \bar{\eta}_{CO} C_i^h}{\frac{1}{\bar{\eta}_{CO}} + \frac{\Delta H_1}{Q_{C_t}} + 1} \quad \textbf{(3)}$$

The calculated values of both minimum coke consumption (K_{min}) and minimum carbon in coke (C_{min}) could be estimated from Fig.1 using the value of r_{dmin} as the following:

$$C_{\min} = \frac{1 - r_{d_{\min}}}{\bar{\eta}_{CO}} - 2n\frac{\bar{\eta}_{H_2}}{\bar{\eta}_{CO}} - n \quad ,$$

$$K_{\min} = \frac{C_m + C_e}{C_k} \quad \textbf{(4)}$$

(where C_k = carbon content in coke, and C_e = carbon content in hot metal).

These developed models can be used to investigate and further predict the effect of different factors on the relative coke consumption of iron blast furnaces, such as iron ore composition and natural gas injection, and also on the efficiency of blast furnace operation itself.

For example, increasing Si content in hot metal will increase coke consumption by 2.25 kg (coke)/0.1% [Si], as shown in Table 1. Furthermore, as shown in Table 2, the amount of slag significantly affects the relative coke consumption (slag amount mainly depends on the composition of iron ore sinter).

Table 1 Effect of [Si] content in hot metal on the relative coke consumption

n, mol(CH_4)/mol(Fe)	0.00634	0.01058
[Si], %	0.3	0.5
r_{dmin}, mol(Fe_d)/mol(Fe_o)	0.480	0.473
C_m, mol (coke carbon)/mol (Fe)	1.625	1.650
K_m , kg (coke)/tHM	437	441.5

Table 2 Effect of slag amount on the relative coke consumption

Slag amount, U, kg(slag)/t HM	r_{dmin}	C_m	K_m	ΔK/ΔU, kg (coke)/kg (slag)
150	0.505	1.547	0.419	-
250	0.495	1.577	0.426	0.070
350	0.486	1.607	0.433	0.069
450	0.476	1.636	0.440	0.70
550	0.467	1.666	0.447	0.069

A complete roadmap was demonstrated [9] by the author of the present work to change the operation regime of iron blast furnaces working on composite blast technology, as shown in Fig.2. The ratio of oxygen to natural gas injection determines the value of theoretical flame temperature (TFT) and degree of direct reduction of iron oxides (r_d). Both indices show the effectiveness of the application of composite blast technology in blast furnaces. The operators of BF always use these indices as a fundamental furnace–control parameters. The roadmap steps in Fig.2 can be used to investigate the effect of different operating parameters on the value of r_d and TFT.

2.2. Alternative ironmaking technologies

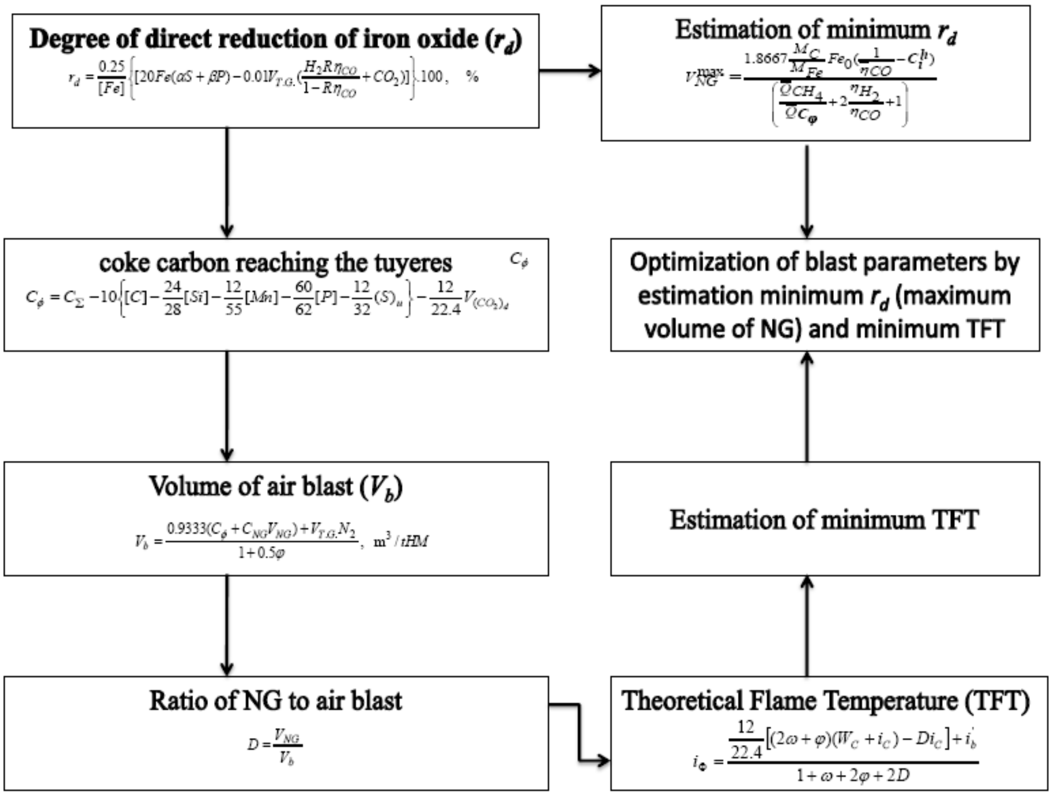

Fig. 2 Roadmap steps to change the blast parameters of iron blast furnaces operated with natural gas injection [9]

The alternative ironmaking processes rather than BF offer some processing advantages to become competitive with traditional iron blast furnaces. They use coal rather than coke, fines rather than sinter, small-scale operation, lower capital cost, and best environmental control [13]. In many countries, direct/smelting reduction processes (DR & DS) are used to make molten, slag-free iron instead of iron blast furnaces. The main target of developing these processes was utilizing non-coking coal in reduction reactions. Besides, some techniques produce smaller quantities of molten metal from iron oxide feedstocks without palettization. The direct reduction processes have solid DRI, which competes with scrap as a metallic charge for electric steelmaking. Smelting reduction processes compete with coke-based blast hot metal production. DR processes can be classified into many techniques as gas-based direct reduction processes (Midrex, HyL, Danarex, Finmet, and Circored) and coal-based processes (rotary kiln, rotary hearth, and multiple-hearth furnace). The only SR processes operated industrially are the Corex process and its variant Finex based on fine ore input [14].

2.2.1. Direct Reduction processes

The concept of DR is more than 60 years old, but the first commercial plants were built in the late 1960s. The direct reduction technique includes many processes in which iron ore is reduced, and either solid or gaseous reducing agents remove oxygen. Reformed natural gas (NG) or non-coking coal is mainly used as the reductant and the primary energy source. The main goal of the process development has been to avoid using coke and consequently reduce the operating costs and decrease greenhouse gas emissions. Generally, the direct reduction process is happened in a furnace by reducing gas to produce DRI - sponge iron. If DRI is charged from the method under hot conditions, it can be immediately briquette into hot briquetted iron (HBI), which has an advantage in shipping, storage, and handling.

The significant processes of the direct reduction technique can be summarized in the following categories according to the type of furnace [3,15-18];
(i) Shaft furnace techniques: gas-based processes using reformed natural gas as the reductant, such as in Midrex and HYL I and III.

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(ii) Fluidized bed techniques: gas-based processes in fluidized bed reactors such as Fior, Finmet, Circored, and iron carbide process.
(iii) Rotary kilns and rotary hearth techniques: coal-based DR such as SL/RN, COMET, INMETCO, and FASTMET.

According to the 2020 world direct reduction statistics of Midrex, as shown in Fig.3, the annual DRI production was 104.4 million tons (Mt) in 2020 (despite the global COVID-19 pandemic) [19]. Direct Reduced Iron output decreased by 3.4 % from the record 108.1 Mt produced in 2019. The combination of India and Iran made over half of the global DRI [19]. From 2015-2019, worldwide DRI output increased by 35.5 Mt, or nearly 49%, primarily driven by the increase in coal-based DRI in India, the high-capacity utilization of existing and new gas-based plants in Iran, and the ramp-up of new capacity, such as Tosyali Holding's MIDREX® Plant in Algeria. However, the onset of the global COVID-19 pandemic in early 2020 had a ripple effect on DRI production 2020, as well as the completion and start-up of a new cap [WSD: World Steel Dynamic, 2020]. MIDREX Plants produced 62.63 Mt in 2020. The production for 2020 was calculated from the 35.47 Mt confirmed by MIDREX Plants located outside of Iran and 27.16 Mt for the MIDREX Plants in Iran. Over 8.2 Mt of HDRI were produced by MIDREX Plants worldwide. MIDREX Technology continued to account for ~80% of worldwide production of DRI by shaft furnaces. MIDREX Plants have produced a cumulative total of more than 1,165 Mt of all forms of DRI (CDRI, HDRI, and HBI) through the end of 2020.

2.2.2. Smelting reduction processes

SR technology is being used for hot metal production without using coke. These processes mainly depend on using coal directly instead of coke and possibly fine ores instead of pellets or lump ores. So, the advantage of this technique is the lower capital cost results from the elimination of the coke and agglomeration plants and high smelting intensities. Many processes have been developed under different commercial names, such as Corex, Finex, HIsmelt, Technored, and others [2.3, 14-15]. The most common smelting reduction process that reached industrial applications is Corex and Finex processes.

Corex process has already been commercialized in at least three installations in the world, South Africa, Korea, and India, each with a capacity of 0.6 Mt/y. The process does not use coal directly or fine ores; since the reduction is made in the solid state, it has a low smelting intensity; consequently, its capital costs are similar to the BF. The Corex process at the POSCO Pohang works (Korea) has been successfully operated with 600,000 tons of pig iron production per year and reconstructed to the Finex configuration. A new Corex module was constructed at Baosteel in Chain with an average capacity of 1.5Mt/y. The process is generally composed of two main reactors. One is the pre-reduction furnace that reduces iron ore to 90%. The other is a Melter - gasifier that finally reduces and smelts the iron ore and generates reducing gas by coal combustion for the pre-reduction furnace [20-25]. Many complicated chemicals and mass transport occurred in this reactor. The cost efficiency of the Corex process is enhanced using the leading gases that can be utilized in power generation or exported to the neighboring direct reduction plant. This situation is already applied at the Corex plant of Saldanha Bay in South Africa. Dust emissions from the Corex plant are significantly less than in the traditional production route. The dust content of the export gas is less than 5 mg/Nm^3. Most of the dust captured in the gas cleaning system is

Total World Production: 104.4 Mt

	2018	2019	2020
MIDREX®	61.5%	60.5%	60.0%
HYL/Energiron	15.7%	13.2%	12.4%
PERED	2.4%	2.1%	2.9%(e)
Other	0.2%	0.2%	0.2%
Rotary Kiln	20.2%	24.0%	24.4%

(e)estimated Source: Midrex Technologies, Inc.

2020 Top 5 DRI Producing Nations

COUNTRY	PRODUCTION (Million Tons)
India	32.98
Iran	30.21
Russia	7.93
Saudi Arabia	5.19
Mexico	5.17

Source: World Steel Association, SIMA, and Midrex Technologies, Inc.

Fig.3 Statistical analysis of Midrex for world DRI/HBI production [19]

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recycled. The Corex process has high specific coal consumption and a relatively large off-gas flow with a medium-high calorific value. Using this off-gas as an energy source largely determines the energetic efficiency of the process.

The Finex process is the developed module of Corex technology. The FINEX plant consists of two technological core units. A four-stage reactor system consists of bubbling fluidized beds (instead of a shaft reduction unit of Corex) and a Melter gasifier. The fine iron ore, after drying, is charged into a series of fluidized bed reactors together with fluxes such as limestone or dolomite. The iron-ore fines pass downward through four reactors, heated and reduced to DRI using hot reducing gas. The DRI fines are hot compacted to HCI (hot-compacted iron) and then transferred to a charging bin positioned above the Melter gasifier in which the HCI is melted to hot liquid metal.

2.3. Further innovative ironmaking processes

The new trends in ironmaking processes that begin to be implemented should be more radical than those discussed above to be competitive with the conventional blast furnace process. Further innovative trends in ironmaking processes were discussed in many kinds of literature [15, 26, 27-40]. A combination of the two approaches may overcome the difficulties of a single process. The 2-step ironmaking process using pellets and coal has been adopted using a reduction shaft furnace (or rotary hearth furnace) and Melter-gasifier. The operation is more straightforward than a blast furnace because of no liquid-state cohesive zone. Various investigators have analyzed a combination of FASTMET composite pellet process and direct smelter process. The FASTMET process suffers from low specific productivity and the separation of the ore gangue and coal ash from the iron. Direct smelting is limited by energy generation and post-combustion limitations. The Melter- gasifier condition is sometimes unstable owing to the reduction degree of DRI, the flux calculations, and the coal's physicochemical characteristics. A very high basicity slag usually has a high melting point. Its viscosity varies significantly under the furnace conditions, resulting in slag formation problems. However, lowering the required reduction and completing reduction and melting, which separates the gangue in a smelter with modest post-combustion, overcomes the issues associated with the individual processes.

Another process combination between iron and steelmaking in one process is the IFCON process, developed in South Africa and currently operated at ISCOR. Coal and fine iron ore fed into the top of a cylindrical furnace with channel induction heaters similar to a hot metal mixture. The off-gases from the devolatilization of the coal and the reduction reaction are post-combusted, supplying most of the energy to melt the material and complete the reduction. A unit capable of producing steel containing 0.1 % C at a rate of 200,000 tonnes or more per year has already been begun by ISCOR in Pretoria. Although the productivity seems to be low compared with BF, combining the coke plant, sinter plant, BF plant, and steel plant in one single process is extremely attractive.

Many new direct reduction processes have been developed and commercialized by Finmet, Circored, Circofer, Spirex, Arex, Fastmet, Inmetco, and Comet. All of these processes have its own advantages, and it is impossible to make a general cost comparison between different approaches. Often the development of a new process for ironmaking is motivated by a new way to utilize energy, either by a decreased use or a cheaper source. Generally, the possibility of large-scale production, high specific volume production, and simplicity are essential for a process concept to be successful.

The raw materials required for ironmaking (lump ore, sinter, pellets, ore fines- coal, coke, natural gas and limestone-dolomite) play a pivotal role in developing new ironmaking processes. Raw materials constitute at least 60% of the cost of hot metal or other iron metallic. The availability of raw materials would determine the choice of the appropriate process. However, to curtail costs and improve flexibility, the trend which has already emerged and will undoubtedly continue exhibits the advent of process combinations that exemplify a shift from lump ore to fine ore, from metallurgical coal to natural gas or non-coking coal, and from scrap-to-scrap substitutes. Furthermore, a new trend for using acceptable ore/ steel plant wastes as secondary resources has been developed.

The production capacity is also a factor in developing iron and steelmaking. The alternative technologies have to cover a large capacity spectrum in the years ahead. Midrex company is starting with a unit size of 400,000 tpa; today, mega modules for 2.0-2.5 Mtpa are available. Corex is also increased in size from 1000 tpd to 3000-4000 tpd individual units.

Minimizing energy consumption will greatly influence the gross energy consumption of any company. Ironmaking researchers are trying their best to reduce energy consumption by introducing new ironmaking techniques and developing mathematical

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models to measure and control different operation parameters of alternative ironmaking processes. Searching for innovative high-efficiency blast furnaces with lower energy consumption is now the main target of BF researchers to develop a new blast furnace. To realize this idea, as mentioned previously, for example, creating a new reactor to link the ironmaking process with steel making process in which the released heat from the steel process will provide the heat for the ironmaking process or lowering the chemical reaction temperature and reduce most waste energy and recovery all the possible waste energy for blast furnace or/and improving the blast furnace shape and size, etc. Fundamental research in ironmaking processes will enhance and support all these new ideas and trends.

Environmental problems in ironmaking processes should also be considered. The iron and steel life cycle emission represents about 4.6 % of the total global CO_2 emissions (greenhouse gas, GHG). An increase of GHG concentrations in the atmosphere threatens climate change. In the United Nations Framework Convention on Climate Change framework, countries have agreed to reduce GHG emissions. The cost of CO_2 removal ranges from 10.3 to 18.5 US $/ t of CO_2. Significant investments in pollution control measures and technological changes, particularly in coke and sinter-making, should be addressed. However, the alternative ironmaking processes, which do not require either coke or sinter are preferable.

3. Ironmaking and nanotechnology

A novel idea developed by the author of the present work [41-42] is to use nano-sized iron oxide in ironmaking processes. Different methods can synthesize nano-sized iron oxide particles with unusual and specific properties and can be considered a promising source for decreasing energy consumption in ironmaking processes. The nanopowder could be charged to a blast furnace together with the blast, much like the current pulverized coal injection technology. Further, there may be other reactors in which the nano-sized particles can be reduced, such as a flash furnace or a cyclone reactor. The reducibility of iron oxide nanoparticles with hydrogen gas was investigated isothermally under different operation conditions. The influence of reduction parameters on the structural characteristics of the produced products was extensively studied to get a thorough, comprehensive study of the reduction process.

4. Conclusion

The conventional blast furnace is still the principal means of hot metal production. However, there is a significant revolution to develop new ironmaking technologies with high-intensity production of iron at a relatively lower cost, based mainly on direct and smelting reduction processes. Improvements of these technologies will continue to achieve the best performance in energy consumption and greenhouse gases emission reduction. Natural reduction processes produce solid direct reduced iron (DRI) and/or hot briquette iron (HBI) which compete with scrap as metallic charge for electric steelmaking. Smelting reduction processes compete with coke-based blast hot metal production. The presence of cheap natural gas in some areas like Latin America, Middle East, North Africa, and the Pacific Rim makes DRI very competitive to blast furnace hot metal and scrap. The main benefit of the direct and smelting reduction processes is that the unit uses natural gas or coal as a fuel. Thus, a coke oven plant is no longer needed, significantly reducing the emission of gases. Furthermore, these technologies offer processing advantages such as using iron ore fines rather than sinter, economical operation at a small scale, lower capital cost, flexibility in process and materials use, and greater environmental control.

There has been a rapid increase in the production of iron via direct reduction processes in the last forty years. According to the 2020 world immediate reduction statistics of Midrex, the annual global Direct Reduced Iron (DRI) production in 2020 was 104.4 million tons (Mt) despite the global COVID-19 pandemic. DRI output was down 3.4 % from the record 108.1 Mt produced in 2019. Further growth of DRI production is still expected in the next few years.

There are still many future challenges for developing the iron and steel industry to save energy and reduce CO_2 emissions. The combination of more than one ironmaking process, the use of low-grade iron ores in DR plants, the increase in the production capacity of DR and DS plants, using nano-sized iron oxides, and the developed new energy resources are the main ideas now being investigated by iron and steel producers all over the world to enhance the efficiency of ironmaking processes.

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