MIDRE$X^{®}$ Processes

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Since 1978, when a plant based on the MIDREX process was built in Qatar for producing direct reduced iron, Kobe Steel and MIDREX Technologies, Inc., have collaborated to make many technical improvements in the process. The largest MIDREX module, having an annual production capacity of 1.8 million tones, began operation in 2007. The MIDREX module, together with a melt shop, now has a production capacity comparable to that of a blast furnace. This paper presents an overview of the history of the technical developments in these processes, as well as the latest developments in this field.

Introduction

MIDREX direct reduction ironmaking (hereinafter referred to as the "MIDREX process") reduces iron ore using natural gas. The original process was developed by the Midland-Ross Co., which later became MIDREX Technologies, Inc. (hereinafter referred to as "MIDREX Technologies"), a wholly owned subsidary of Kobe Steel. A pilot plant was built in Toledo, Ohio in 1967. The first commercial plant, having a production capacity of 150 thousand tonnes/year, was built in Portland, Oregon, in 1969.

The process was immature in 1978, when Kobe Steel began the construction of a plant with a production capacity of 400 thousand tonnes/year in the State of Qatar. Kobe Steel significantly modified the design, exploiting the company's technologies developed through blast furnace operation, and stabilized the then new process. On the other hand, MIDREX Technologies also carried out various improvements to the plants they built in various countries. These were all integrated in the early 1980s, making the process nearly complete [1].

The maximum production capacity in 1984, when Kobe Steel became affiliated with MIDREX Technologies, was 600 thousand tonnes/year. Later improvements, made by Kobe Steel in collaboration with MIDREX Technologies, have dramatically increased the production capacity. In 2007, the scale reached 1.8 million tonnes/year, which is comparable to that of a small blast furnace.

1. Characteristics of reduced iron

The MIDREX process produces direct reduced iron (hereinafter referred to as "DRI"). The process reduces iron ore using a reforming gas made from natural gas. The DRI is used mainly as the raw material for electric arc furnaces (EAFs), as a clean iron source substitute for scrap iron.

Pores are left behind in the DRI after oxygen has been removed. These pores, if filled with water, for example, can cause the iron to reoxidize with ambient oxygen, generate heat and occasionally ignite a fire. This makes it difficult to transport the product by ship or to store it in the open air over an extended period of time. To resolve this issue, Kobe Steel developed a technology for compacting DRI into briquette iron at a temperature of around 700℃. DRI has an apparent density of 3.4 to 3.6t/m^3, while the briquette iron has an apparent density of 5.0 to 5.5t/m^3.

The reoxidation issue had restricted DRI manufacturing sites to the vicinity of steelmaking plants. The hot briquette technology has eliminated this site restriction, making it possible to build a reduced ironmaking plant where resources such as natural gas, iron ore and power are less costly. The product, hot briquette iron (hereinafter referred to as "HBI"), can be exported by sea to steelmaking plants and rolling mills in other countries. This has expanded the number of potential sites for MIDREX plants all over the world [1].

Table 1 compares the chemical and physical properties of DRI and HBI, while **Fig. 1** shows the appearance of DRI and HBI.

The global production of DRI increased dramatically from 790 thousand tonnes/year in 1970 to 68.45 million tonnes in 2008. DRI made by the

Table 1 Specification of DRI and HBI

	DRI	HBI
Fe total (%)	90～94	←
Fe metallic (%)	83～89	←
Metallization (%)	92～95	←
Carbon (%)	1.0～3.5	←
P* (%)	0.005～0.09	←
S* (%)	0.001～0.03	←
Gang* (%)	2.8～6.0	←
Mn, Cu, Ni, Mo, Sn Pb and Zn (%)	trace	←
Bulk density (t/m^3)	1.6～1.9	←
Apparent density (t/m^3)	3.4～3.6	5.0～5.5
Discharge temperature (℃)	40	80

* depends on components of iron ore

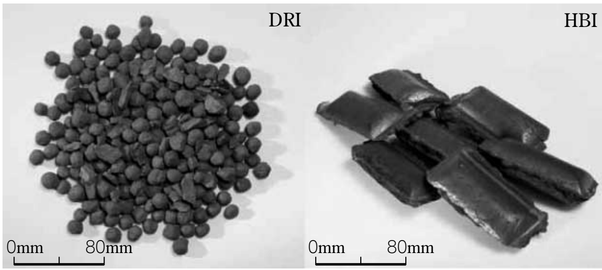

Fig. 1 Appearance of DRI and HBI

58 modules operating & 4 modules under construction in 19 countries.
Total capacity of MIDREX Process=48.4 million ton/y

Fig. 2 World's MIDREX plants

MIDREX process accounts for about 60% of global production.

Fig. 2 shows the worldwide locations of MIDREX plants.

2. MIDREX process

Fig. 3 is a flow chart for the MIDREX process. Either lump ore, or pellets prepared for direct reduction ironmaking, are charged as raw material from the top of a shaft furnace. The ore is reduced inside the furnace and the reduced iron is discharged from the bottom of the furnace. Reductant gas blown in from about the middle of the shaft furnace reduces the raw material above the nozzle and escapes from the top of the furnace. The cooling gas, which circulates in the lower portion of the furnace, cools the DRI. Both the charging and discharging ports are dynamically sealed by a sealing gas, allowing the continuous charging of raw material and discharging of DRI.

The reaction occurring in the shaft furnace is the well-known reduction reaction of iron, described as follows:

$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$
$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$

The exhaust gas (top gas) emitted from the top of the shaft furnace is cleaned and cooled by a wet scrubber (top gas scrubber) and recirculated for reuse. The top gas containing CO_2 and H_2O is pressurized by a compressor, mixed with natural gas, preheated and fed into a reformer furnace. The reformer furnace is provided with several hundreds

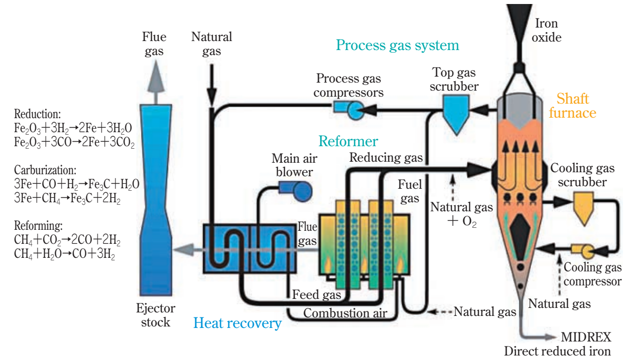

Fig. 3 MIDREX process flow sheet

of reformer tubes filled with nickel catalyst. Passing through these tubes, the mixture of top gas and natural gas is reformed to produce reductant gas consisting of carbon monoxide and hydrogen. The reaction that occurs in the reformer tubes is as follows:

$CH_4 + CO_2 \rightarrow 2CO + 2H_2$
$CH_4 + H_2O \rightarrow CO + 3H_2$
$2CH_4 + O_2 \rightarrow 2CO + 4H_2$
$CO + H_2O \rightarrow CO_2 + H_2$
$CH_4 \rightarrow C(S) + 2H_2$

3. History of the development of the MIDREX process

3.1 Operation of MEGAMOD® shaft furnace: Raw material coating (1990 -)

There was an urgent need to upsize the shaft furnace in response to the market need for an increased production capacity. To achieve this, Kobe Steel and MIDREX Technologies began development by

- conducting analyses using the three-dimensional finite element method,
- conducting two-dimensional model experiments for verification and
- improving raw material characteristics on the basis of reduction/pulverization tests.

As a result, the shaft diameter was increased to 5.5m and then to 6.5m (MEGAMOD shaft furnace). This has increased the production capacity from the previous maximum of less than 400 thousand tonnes/year, first to 800 thousand tonnes/year, and then to 1.5 million tonnes/year [1].

A technology was devised to raise the temperature of reducing gas (bustle gas) by coating the raw material with lime hydrate which has a melting point higher than that of DRI. This has raised the reducing gas temperature to about 900℃ and improved shaft furnace productivity by more than 10%.

3.2 Oxygen injection into reducing gas (2000 -)

Injecting high purity oxygen into the hot reducing gas has further raised the reducing gas temperature to about 1,000℃ (**Fig. 4**). Although a portion of hydrogen and carbon monoxide is consumed by combustion with oxygen, raising the temperature of the reducing gas has improved shaft furnace productivity by 10 to 20%[2), 3)].

3.3 Improvement of oxygen injection technology (2005 -)

The oxygen injection, described above, has evolved into an improved technology, called "OXY +®", which was made possible by the introduction of a partial combustion technique. As shown in **Fig. 5**, the OXY + employs a combustor in addition to the reformer. The combustor partially burns natural gas and oxygen to produce hydrogen and carbon monoxide, which are added to the reducing gas generated by the reformer[2), 3)].

Fig. 6 shows the transition of shaft furnace productivity.

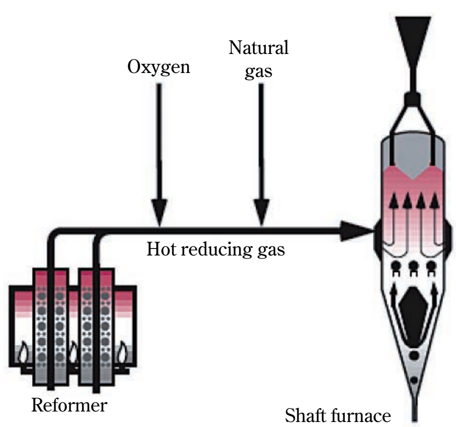

Fig. 4 Oxygen injection flow

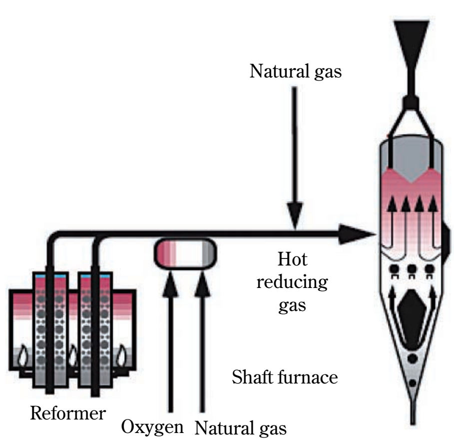

Fig. 5 OXY+ flow

3.4 Development of a shaft furnace, SUPER MEGAMOD®, and enhancement of engineering (2007-)

The experience of operating the shaft furnace with a diameter of 6.5m has led to the construction of a larger shaft furnace at Saudi Iron & Steel Company in Hadeed, Saudi Arabia in 2007. This shaft furnace has a diameter of 7.15m and an increased production capacity of 1.8 million tonnes/year (**Fig. 7**).

Another shaft furnace, SUPER MEGAMOD, currently under development, is to have a further increased production capacity in the range of 2 million tonnes/year. The increased size of the shaft furnace enlarges the entire facility, which requires even more sophisticated design and construction

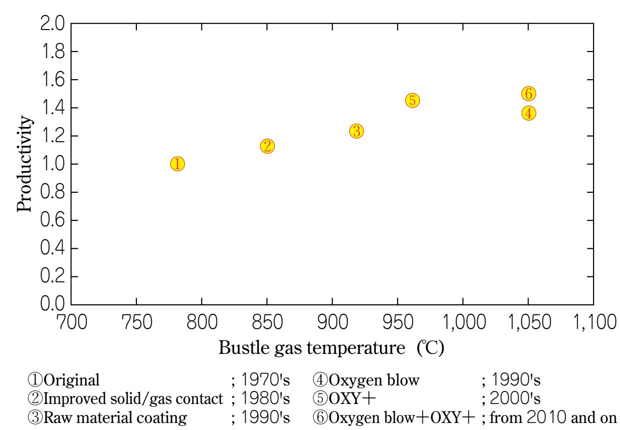

Fig. 6 Changes in productivity of MIDREX shaft furnace

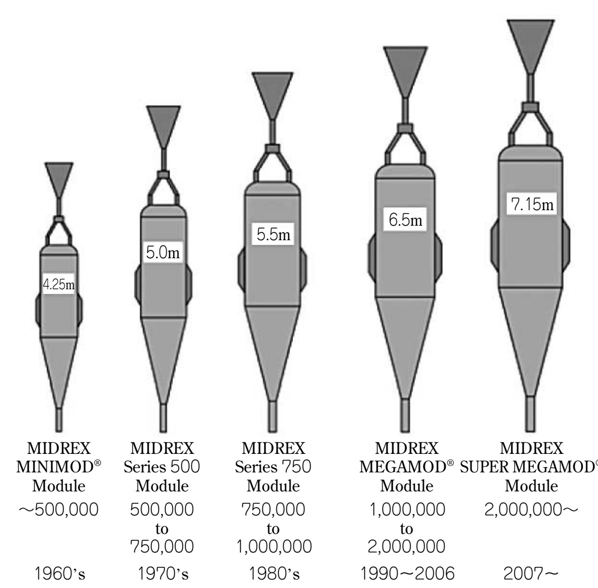

Fig. 7 Changes in shaft furnace diameter and annual production

management. Because of this, since 2004, a three-dimensional CAD has been adopted for the entire designing process. The three-dimensional CAD allows the retrieval of structural calculation data, as well as the direct output of isometric drawings of piping and material spreadsheets. The three-dimensional CAD is also utilized at construction sites for planning construction schedules. **Fig. 8** is a three-dimensional CAD drawing showing an entire DR Plant for Qatar Steel.

3.5 Delivery record

Table 2 shows the delivery record of MIDREX plants. The following is an outline of the major plants.

3.5.1 LION plant

This plant with a rated capacity of 1.5 million tonnes/year was constructed for the Lion Group, Malaysia, and began operations in 2007 (**Fig. 9**)[4]. It produces two types of products, hot DRI (HDRI) and HBI. The HDRI is supplied as hot metal to a neighboring EAF facility by a hot transport vessel. The HBI is mainly exported and is occasionally used by the neighboring EAF facility.

3.5.2 HADEED Module-E plant

This is the world's largest MIDREX plant. Constructed at the Saudi Iron & Steel Company in Hadeed, Saudi Arabia, it began operations in 2007 (**Fig.10**)[4]. The plant was the first to adopt a shaft

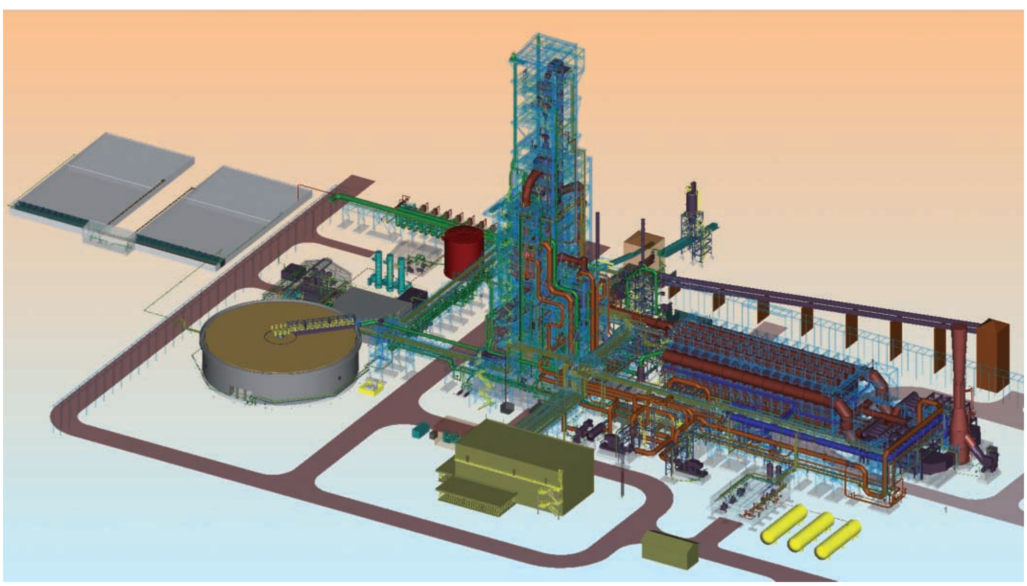

Fig. 8 CAD drawing of QASCO Module-II plant

Table 2 Recent delivery record of MIDREX plants

	Plant	Location	Capacity (million tont/y)	Start up
*	EZDK III	Egypt	0.8	2000
	Essar Steel Module-IV	India	1.0	2004
	Nu-Iron	Trinidad	1.6	2006
	Essar Steel Module-V	India	1.5	2007
	HADEED Module-E	Saudi Arabia	1.76	2007
*	QASCO Module-II	Qatar	1.5	2007
	LGOK Module-II	Russia	1.4	2007
	Al-Tuwairqi Damman	Saudi Arabia	1.0	2007
	LION	Malaysia	1.54	2008
	Essar Steel Module-VI	India	1.8	2009
*	SHADEED	Oman	1.5	2010
	ESISCO	Egypt	1.76	2010
	Al-Tuwairqi Pakistan	Pakistan	1.28	2010

*: Kobe Steel constructed

Fig. 9 LION plant

furnace having a diameter of 7.15m and has a rated capacity of 1.8 million tonnes/year. This capacity is comparable to that of a small blast furnace. The plant produces both HDRI and DRI. The HDRI that it produces is supplied as hot metal directly to a neighboring EAF facility, being transferred by a hot transport conveyor. The DRI is stored temporarily in a silo and supplied to the neighboring EAF facility as necessary.

3.5.3 QASCO Module-Ⅱ

This plant with a rated capacity of 1.5 million tonnes/year was constructed by Kobe Steel at Qatar Steel Company in the State of Qatar and began to operate in 2007 (**Fig.11**). It is to be noted that in 1975 Kobe Steel delivered a plant, Module-I, with a rated capacity of 400 thousand tonnes/year, to Qatar Steel Company. The design and operational improvements that Kobe Steel made on the MIDREX process, which was still immature at the time, have stabilized operations. This plant has won high acclaim and led to an order for Module-Ⅱ.

The Module-Ⅱ plant produces both DRI and HBI. The DRI is supplied to a neighboring steelmaking plant, while the HBI is exported. The DRI is melted at the steelmaking plant and is supplied to a rolling mill that produces billets, rebars and wire rod coils to be exported.

Fig.10 HADEED Module-E plant

Fig.11 QASCO Module-II plant

Fig.12 SHADEED plant

3.5.4 SHADEED plant

In 2008, Kobe Steel completed construction of a plant with a capacity of 1.5 million tonnes/year at SHADEED Iron & Steel Co. in Oman (**Fig.12**). The plant, which is to produce DRI and HBI, is currently in the preparation stage. It is the first plant to adopt a method called HOTLINK® for supplying HDRI to an adjacent EAF by gravity.

4. Recent technological trend

4.1 Hot discharge of DRI

Conventionally, DRI was cooled before being discharged from the shaft furnace. Technical modifications are being implemented to discharge hot DRI (HDRI) in order to improve the specific energy consumption and productivity of the plant, including the downstream steelmaking process. A combination of two discharge methods, cold and hot, was proposed and implemented to allow flexibility in production planning, which improves productivity[3), 5)].

Fig.13 depicts the overall flow in an integrated steel mill equipped with a MIDREX plant. The following three methods (**Fig.14**) allow the transfer of HDRI from the shaft furnace to the downstream steelmaking plant:

a) transfer and supply by a hot transport vessel (Fig.14-①)
b) transfer and supply by a hot transport conveyor (Fig.14-②) and
c) supply by gravity (HOTLINK) (Fig.14-③ and **Fig.15**).

The HDRI discharge methods have been adopted by various plants as summarized in **Table 3**.

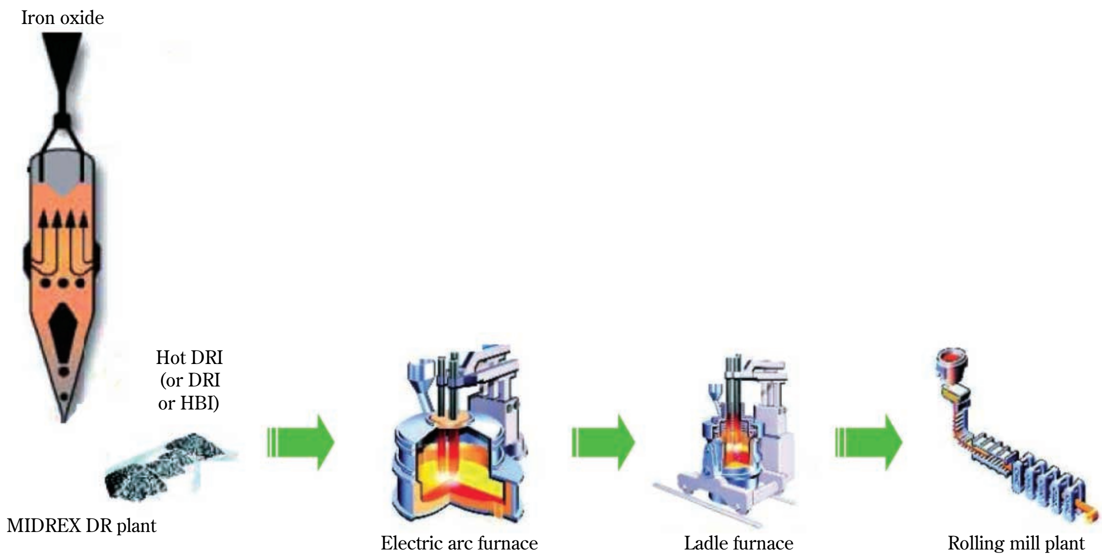

Fig.13 Overall flow sheet for integrated steel mill equipped with MIDREX plant

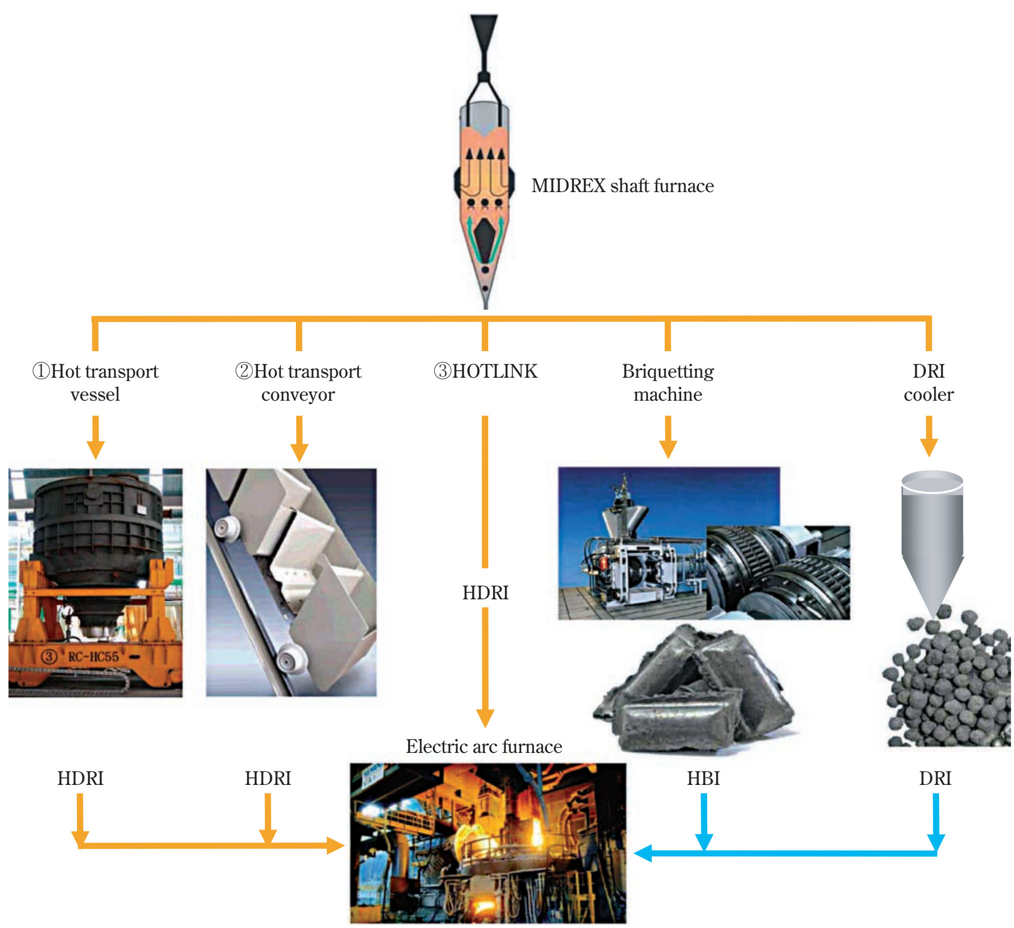

Fig.14 Variation of discharging products

4.2 Improving specific energy consumption and productivity using HDRI

Supplying HDRI at an elevated temperature directly to a steelmaking plant significantly improves the specific energy consumption and productivity of the plant. As shown in **Fig.16**, raising the HDRI supply temperature saves power consumed by the electric arc furnace (EAF). In addition, this power saving reduces the consumption of the EAF's electrode, which decreases the operational cost (**Fig.17**).

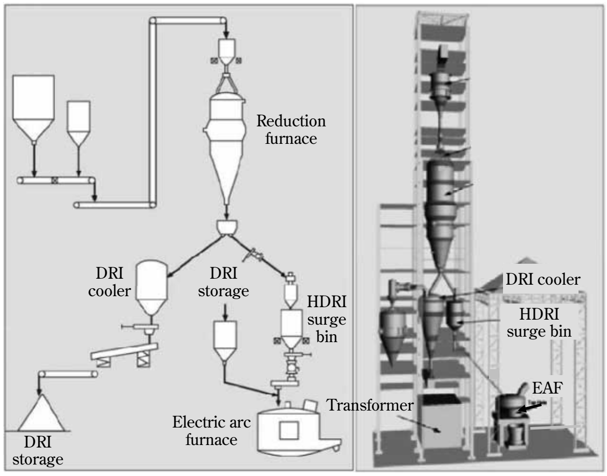

Fig.15 Material flow of HOTLINK and equipment arrange

Table 3 MIDREX plants discharging HDRI

PLANT	LOCATION	START-UP	TYPE SYSTEM
Essar steel Module-I, II, III, IV	India	1999～2004	Hot transport vessel
HADEED Module-E	Saudi Arabia	2007	Hot transport conveyor
LION	Malaysia	2008	Hot transport vessel
ESISCO	Egypt	2010	HOTLINK
SHADEED	Oman	2010	HOTLINK

Furthermore, charging HDRI to an EAF shortens the cycle time of the EAF, which increases the production volume by 10 to 15%.

4.3 CO_2 emission reduction

Various improvements have been made to the MIDREX process to reduce the specific energy consumption of the process, including downstream steelmaking, and to improve the productivity of the shaft furnace. These energy-saving measures not only decrease the operational cost, but also decrease the environmental burden with reduced emissions of CO_2 and other types of exhaust.

The MIDREX process, which is based on natural gas, emits intrinsically less CO_2 than other processes using coal. Because of this, the MIDREX process can also contribute to emission reduction in coal based ironmaking processes. For example, charging HBI produced by a MIDREX plant into a blast furnace reduces CO_2 emissions as a whole.

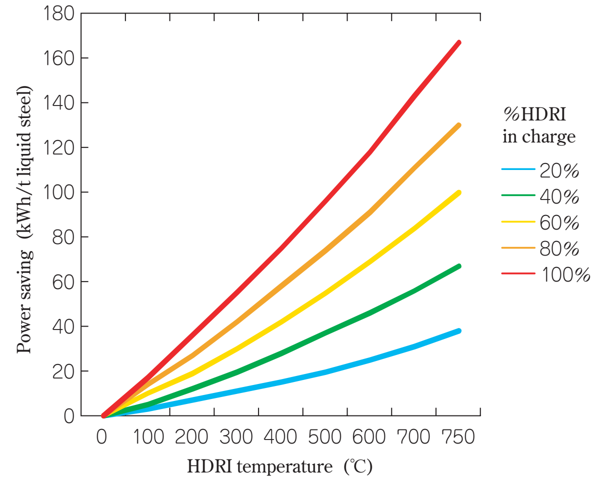

Fig.16 Correlation between HDRI temperature and power savings at EAF

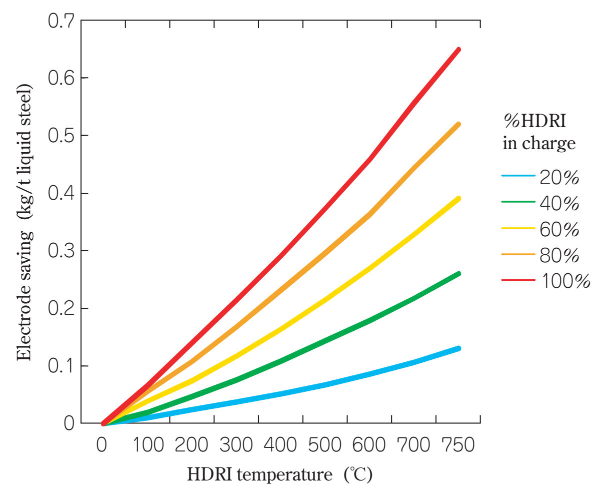

Fig.17 Correlation between HDRI temperature and electrode savings at EAF

4.4 Combination with coal-based fuel

The MIDREX process can utilize not only the reducing gas modified from natural gas, but also coke oven gas and other reducing gases derived from PET coke or from bottom oil generated in oil refineries. Thus the construction of MIDREX plants, formerly restricted to sites in natural gas producing countries, no longer suffers from such limitations. For example, the MIDREX process can be incorporated into a blast furnace based ironmaking facility that has a coking process. The HBI produced by using the coke oven gas can be charged into the blast furnace to decrease the reduction load of the blast furnace. This will decrease the ratio of the reductant used as a heat source (reductant ratio) and reduce CO_2 emissions.

Fig.18 depicts the process flow of the MIDREX process combined with a gasification plant.

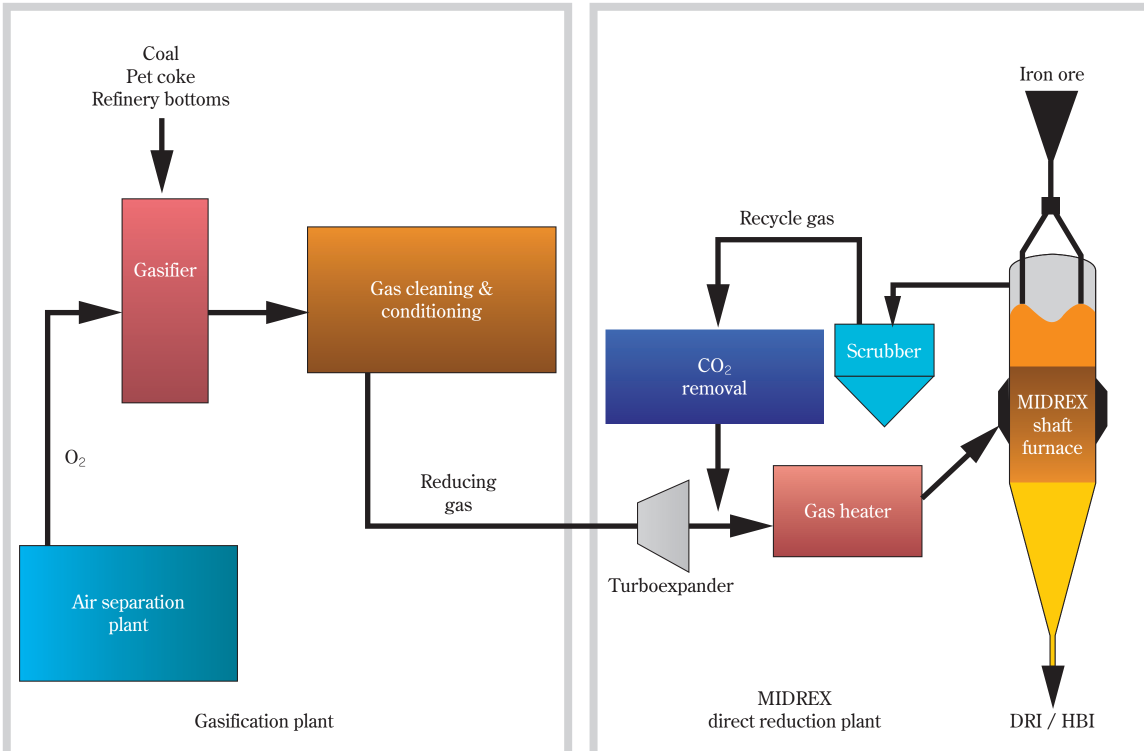

Fig.18 Process flow of MIDREX process combined with coal gasification plant

Conclusions

The origin and development of the MIDREX process have been introduced along with the new technologies that have been developed or are presently being developed by Kobe Steel.

Since the inauguration of the first commercial plant in 1969, seventy-two MIDREX plants have been built in twenty-one countries so far. The MIDREX process occupies a market share of about 60% among DRI making plants. This is a result of the improved reliability of the MIDREX process, as well as improved process efficiency, which is widely recognized and highly evaluated.

Kobe Steel will continue striving to decrease the environmental burden, increase the versatility of raw materials and further improve efficiency so as to contribute to the world's iron and steel production.

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