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Technical Note

Optimization of Sponge Iron Production in Direct Reduction Plants With The KIPEX Method

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ABSTRACT

Due to internationally agreed commitments to reduce production and CO_2 emissions in various industries, including steel and sponge iron production through various direct reduction processes such as Midrex, these processes are now being used and developed worldwide more than ever. However, the technological complexity in this area, resulting from a multitude of control parameters and the intricate cause-and-effect relationships between these parameters, means that different plants around the world produce under slightly different quantitative and qualitative conditions.

This article aims to educate stakeholders that it is possible to produce sponge iron with improved quantity and quality by highlighting the successful results of leading direct reduction plants in this context. It then explains how this goal can be achieved by relying on indigenous and certified technical knowledge such as KIPEX, which is able to implement automation levels 1 and 2. The introduction of KIPEX technology in sponge iron production has led to significant improvements. The production rate increased from 115 to 125 tons per hour, with metallization increasing from 92.088% to 93.77%. The carbon content fell from 1.3% to 1.28%, and the process gas throughput was reduced from 109,500 Nm^3/hour to 107,000 Nm^3/hour. These improvements mean higher productivity, quality, and efficiency in the production of sponge iron.

1. Introduction

In the present era, the reduction of production and CO_2 emissions in industries, such as steel and sponge iron production, has become a global priority. Direct reduction methods, such as Midrex, are being widely adopted and developed to address these commitments [1, 2]. However, the practical application of these methods faces challenges due to complex control parameters and cause-and-effect relationships [3, 4].

Iron ore pellets play a crucial role in direct reduction processes, undergoing chemical transformations in shaft furnaces [5]. Various models have been proposed to describe the gas-solid reactions involved, from basic shrinking core models to more complex pore and grain models [6, 7].

The focus of this article is to explore the feasibility of producing sponge iron with enhanced quantity and quality, drawing on successful outcomes from leading direct reduction plants [8]. Additionally, the potential of relying on indigenous technical knowledge, such as KIPEX, is

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discussed to implement automation and optimize production capacity [9].

The theoretical understanding of many chemical mechanisms involved in midrex and pered technologies (as closely related technologies) is clear and transparent to experts in the field of direct reduction worldwide. However, the practical and integrated application of these mechanisms under real-world conditions presents a challenge, as the behavior and cause-and-effect relationships vary between these mechanisms. In some cases, this leads to unconventional and detrimental labeling of optimal production thinking for direct reduction plants compared to their rated capacities.

Iron ore pellets, which in direct reduction (DR) are roughly round and typically 7–15 mm in diameter, are industrially produced from irregular hematite grains of around 20 µm in size. In a shaft furnace, these pellets undergo a chemical transformation from hematite to magnetite, wustite, and iron [10]. This reduction process takes place at temperatures between 600 and 950 °C and involves six gas-solid reactions on a microscopic scale. Various models to describe these gas-solid reactions can be found in the literature, ranging from simple models for a non-reacting shrinking core to more complex pore and grain models (Fig. 1.).

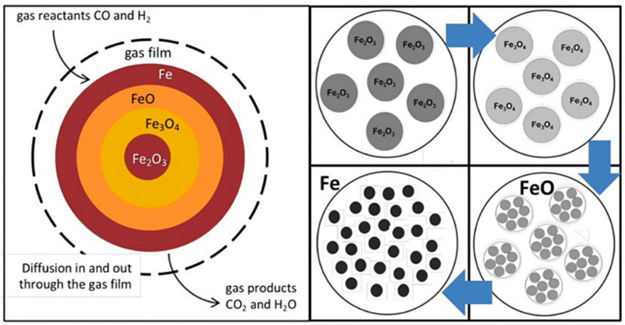
In direct iron reduction, the shaft furnace (Fig. 2.) serves as the centerpiece of this process. In this furnace, iron pellets enter from above and move downward due to gravity; at the same time, they encounter an upward flow of gas (counterflow).

The reducing gas, which consists of CO and H_2 as well as CH_4, CO_2, and H_2O at a temperature of around 950 °C, enters the furnace as an enveloping flow from the middle height and leaves it from the top. Cold natural gas is fed into the lower conical part of the furnace to cool the iron pellets.

The upper part of the furnace, which comprises the reduction zone and the intermediate zone, is cylindrical and has typical dimensions of around 15 and 5 meters in height and diameter, respectively.

In this article, the initial focus is on clarifying the volumetric gas stoichiometry needed to straightforwardly produce one ton of sponge iron. Subsequently, the article calculates the actual consumption of the reducing gas in a 0.8 million t/yr Midrex direct reduction plant for producing one ton of sponge iron under real conditions. This is then compared with the previously mentioned stoichiometric quantity, revealing an approximate 209% difference. The analysis that follows assumes the availability of the reducing gas beyond stoichiometric quantities in all direct reduction plants. The article explains that optimizing the thermodynamic and kinetic conditions within these plants' furnaces could enhance the reducing gas's achievable efficiency, consequently leading to increased production relative to their nominal capacities.

This discussion continues with a detailed examination of the performance of scattered Midrex plants worldwide to pursue the following objectives:



(a) (b)

Fig. 1. Evolution of the pellet structure along with reaction: (a) Unreacted Shrinking Core Mode; (b) Grain Model. The porous structure evolution (b) was determined from experimental observations [11, 12].

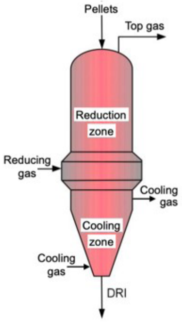


Fig. 2. Schematic layout of a direct reduction shaft furnace [11].

- The possibility of increasing production capacity in global direct reduction plants without hardware modifications.
- The primary factor contributing to the superior production levels of these plants compared to their nominal capacities lies in their relative success in optimizing overall process parameters, particularly the control of thermodynamic conditions within the furnace.
- Because direct reduction plants have fixed costs such as energy and equipment maintenance, producing more sponge iron than the nominal capacity can significantly lower these costs per ton, leading to a higher profit margin.
- Finally, the introduction and overview of KIPEX technical knowledge will be presented as a solution for optimizing direct reduction plants.

2. Method

2.1. Calculation of Stoichiometric Gas Volume Required for Producing One Ton of Sponge Iron

It is acknowledged that the reaction equations for the reduction of hematite to metallic iron are as follows:

$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O \qquad \text{Eq.(1)}$$

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2 \qquad \text{Eq.(2)}$$

Considering the stoichiometry of Reaction 1, the molar masses of the participating substances in the reaction, and considering hydrogen as an ideal gas, it is determined that 428.1 tons of Fe_2O_3 and 600 m^3 of hydrogen gas are required for the production of one ton of sponge iron. Based on Reaction 2, it should be noted that the volumetric consumption of CO gas is identical to that of H_2. The stoichiometric values are provided in Table 1.

2.2. Calculation of the Consumed Volume of the Reducing Gas to Produce One Ton of Sponge Iron

The general specifications of a 0.8 million t/yr Midrex direct reduction plant are primarily considered according to Table 2.

The effective volume of the reduction zone of the furnace is 280 m^3. Iron pellets with a density of 2.1 tons per m3are introduced at the beginning of this zone, and sponge iron with a density of 1.47 tons per m^3 is discharged at the end. Therefore, the average of these two values, equal to 1.785 tons/m^3, can be considered the average density of this zone. Hence, the total weight of the materials in the reduction zone of the furnace is calculated as follows:

$$280\ m^3 \times 1.785\ ton/m^3 = 500\ ton \qquad \text{Eq.(3)}$$

Given a production rate of 105 tons per hour in this plant, the duration required for the production and passage of 500 tons of sponge iron through the reduction zone of the furnace is calculated as follows:

$$500\ ton\ /\ 105\ ton/hour = 4.76\ hour \qquad \text{Eq.(4)}$$

The total volume of the reducing gas utilized is expressed as:

$$194{,}897\ Nm^3/h \times 4.76\ h = 927{,}708\ Nm^3 \qquad \text{Eq.(5)}$$

Therefore, the consumed gas volume per ton of sponge iron will be:

$$927{,}708\ Nm3\ /\ 500\ ton = 1{,}855\ Nm^3/ton \qquad \text{Eq.(6)}$$

As observed above, the actual gas consumption for producing one ton of sponge iron in a direct reduction plant is significantly higher than its stoichiometric quantity (209% more). The numerical difference is equal to:

$$1855 - 600 = 1255\ Nm^3 \qquad \text{Eq.(7)}$$

2.3. Examination of the Difference between Stoichiometric and Actual Reduction Gas Consumption for the Production of One Ton of Sponge Iron

Considering both equilibrium and non-equilibrium

Table 1. Stoichiometric Values for Producing 1 Ton of Sponge Iron.

Component	Fe_2O_3	H_2	Fe	H_20
Value	160 gr/mol	3×22.4 lit/mol = 67.2 lit/mol	2×56gr/mol = 112gr/mol	3×18gr/mol = 54gr/mol
	0.000160 ton	0.0672 m^3	0.000112 ton	
	1.428 ton	600 m^3	1 ton	

reactions happening at the same time in the furnace, each with its own kinetic and thermodynamic needs, we can clearly claim that the specific conditions of these reactions inside the furnace are the main reason for the difference in the amount of reducing gas under real conditions compared to the stoichiometric quantity.

Table 3. and Fig. 3. represent a careful effort to explain the impact of temperature and hydrogen gas concentration variations needed to produce one ton of sponge iron, aiming at understanding the influence of these thermodynamic and kinetic factors on the process. We also discuss some other factors that directly and indirectly affect the conditions inside the furnace, leading to a higher demand for reducing gas.

Table 2. General Specifications of a 0.8 million t/yr Midrex Direct Reduction Plant [13].

Parameter	Value
Furnace Diameter	5.65 m
Reduction zone height	9.75 m
Effective Reduction Zone Volume	279.86 m^3 ~ 280m^3 REFORMER
Number / Diameter of tubes	468 / 200 mm
Process Gas Preheat Temp	410 °C
Combustion Air Preheat Temp	600 °C
Production Rate	105 tons/hour
Process Gas	105,000 Nm^3/h
Reformed Gas	164,716 Normal m^3/hour
Bustle Gas	194,897 Normal m^3/hour
Top Gas Fuel	53,550 Normal m^3/hour
Main Air	162,501 Normal m^3/hour
Flue Gas	209,706 Normal m^3/hour
Natural Gas	2.53 Gcal/t
Electricity	105 kWh/t

Table 3. The Effect of Temperature and Concentration on the Required Volume of Reducing Gas for the Production of One Ton of Sponge Iron [11].

TEMP., K/°C	$FeO \rightarrow Fe$		$Fe_3O_4 \rightarrow Fe$	
	100% H_2	5% H_2O	100% H_2	5% H_2O
900/627	1470 (Nm^3/t Fe)	1799 (Nm^3/t Fe)	1882 (Nm^3/t Fe)	2283 (Nm^3/t Fe)
1000/727	1264 (Nm^3/t Fe)	1500 (Nm^3/t Fe)	1512 (Nm^3/t Fe)	1761 (Nm^3/t Fe)
1100/827	1129 (Nm^3/t Fe)	1314 (Nm^3/t Fe)	1273 (Nm^3/t Fe)	1444 (Nm^3/t Fe)
1200/927	1036 (Nm^3/t Fe)	1189 (Nm^3/t Fe)	1140 (Nm^3/t Fe)	1276 (Nm^3/t Fe)

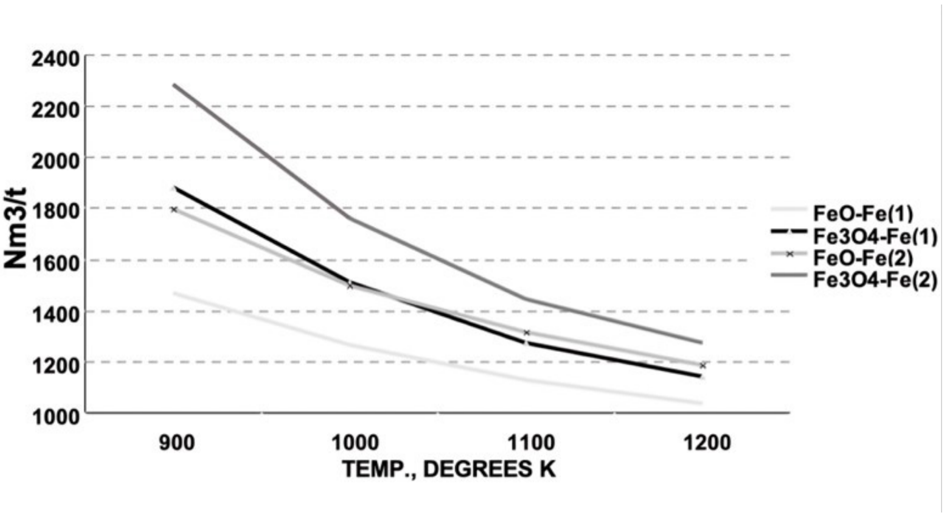


Fig. 3. Plotting the mentioned changes related to Table 3.

- The reducing gas entering the furnace is not 100% pure, and besides hydrogen, it contains impurities such as carbon monoxide, water vapor, methane, carbon dioxide, and occasionally nitrogen. Consequently, these impurities reduce the reductive potential of the gas, resulting in an increased consumption of the reducing gas.
- Part of the introduced reducing gas absorbs and reduces the iron oxide particles present in the furnace atmosphere. However, these reduced particles, along with the gas from the hot and cold cycles, exit the furnace, enter scrubbers, and eventually settle in sludge-settling basins, contributing to a decrease in the efficiency of the reducing gas production.
- Due to the design of the direct reduction furnace, it is evident that the cooling and reducing gas cycles always interact in the transitional zone of the furnace. Depending on the control method adopted by the operator in the control room, there may be interference between these cycles, resulting in changes in the thermodynamic and kinetic conditions within the furnace.
- It is obvious that the conversion of hematite to metallic iron does not occur in a single stage but involves various reactions and stages, each having its own activation energy and specific equilibrium constant. Therefore, the total volume of the reducing gas required to carry out these reactions will not necessarily be 600 m^3.

In conclusion, the observed differences between stoichiometric and actual gas consumption for the production of one ton of sponge iron can be attributed to the dynamic and intricate interplay of thermodynamic and kinetic factors governing the complex set of reactions occurring within the furnace.

2.4. Analyzing Midrex Annual Reports: Understanding the Influence of Optimized Process Parameters

Every year, Midrex publishes performance reports for the plants it oversees. This is a valuable chance for global direct reduction experts to improve their technical knowledge by examining both the obvious and subtle aspects of these reports. This article aims to demonstrate the positive impact of the optimal control of process parameters on increasing production efficiency. It provides performance data for 17 out of the 78 plants mentioned in the 2016 Midrex report (the latest report obtained), as detailed in Table 4.
- Plants 1 and 2 experienced 62% and 32% increases in production, respectively, solely based on process optimization without hardware modifications.
- Both Iranian plants (8 and 9) achieved 3.4% and 12% increases in production, respectively, without hardware changes, which is significantly less than the improvements in Plants 1 and 2 discussed earlier.
- Plants 3, 4, 5, 6, and 7, in addition to process optimization, increased their production by 87%, 41.6%, 72.2%, 219%, and 43.5%, respectively, through oxygen injection. The best record in this group belongs to Qatar Steel 1, producing 476,885 tons more than its nominal capacity.
- Plants 10-12 are classified as those producing less than one million tons and did not reach nominal capacity by the end of 2016. Compared to their nominal capacity, their highest production records were below 4.4%, 17.7%, and 10.5%, respectively.
- Plants 13-17 are all Midrex Mega module plants without hardware changes. Plants 13 and 14 achieved 13.6% and 28.8% increases in production, respectively, while plants 15-17 produced less than their nominal capacity and were below 15%, 23.5%, and 3.8%, respectively.

Table 4. The Review of the Best Annual Production Records for Some Midrex Direct Reduction Plants Worldwide Until 2016 [14].

No.	Plant	Year	Capacity (t/y)	Production (t)	Production Rate(t/h) Efficiency%	Metallization (%)	NG (Gcal/t)	Electricity (kWh/t)	Operating time (h)
1	AM Monteral 2	2014	600,000	977,358	120.6 +62%	94.2	2.52	116	8105
2	COMSIGUA	2004	1,000,000	1,342,234	172.8 +34%	92.9	2.34	103	7767
3	Essar Steel II	2004	440,000	822,562	97.1 +87%	92.7	2.49	123	8472
4	EZDK I	2005	716,000	1,014,400	124.3 +41.6%	93.3	2.35	85	8161
5	OEMK III	2015	415,000	714,987	84.4 +72.2%	94.1	2.59	109	8474
6	Qatar Steel 1	2006	400,000	876,885	102.7 +219%	95.0	2.32	95	8538
7	Mobarakeh Steel A	2010	640,000	918,537	107.0 +43.5%	94.4	2.29	109	8587
8	SJSCo	2016	850,000	878,881	111.4 +3.4%	92.7	2.40	129	7886
9	Arfa Iron & Steel	2014	800,000	895,995	109.9 +12%	90.9	2.43	104	8151
10	DRIC 2	2014	500,000	478,091	57.5 -4.4%	94.3	2.86	136	8319
11	Hormozgan A	2014	825,000	679,130	89.0 -17.7%	93.4	2.68	-	7628
12	Hormozgan B	2013	825,000	738,386	94.1 -10.5%	93.6	2.66	-	7850
13	Hadeed E	2013	1,760,000	2,000,458	236.6 +13.6%	93.7	2.33	112	8453
14	Qatar Steel 2	2015	1,500,000	1,886,825	222.3 +25.8%	94.8	2.35	98	8487
15	Mobarakeh Steel G	2013	1,500,000	1,273,233	152.7 -15%	94.1	2.26	109	8341
16	Mobarakeh Steel H	2016	1,500,000	1,147,297	141.6 -23.5%	94.3	2.24	108	8101
17	Essar Steel VI	2012	1,500,000	1,375,945	169.9 -8.3%	92.2	2.42	158	8098

3. Introduction to KIPEX Technical Knowledge and its Capabilities and Implementation Results

The technical knowledge of KIPEX is the result of four years of research and investigation by the authors of this article in the direct reduction plants in Iran from 2001 to 2005. This knowledge was officially registered in 2009. Successful implementations have been documented in various direct reduction plants across the country. Examples include Module 2 of Khuzestan Steel's direct reduction plant, the launch of Iranians' Sirjan Steel's direct reduction plant, normalization and optimization of production at Gol Gohar Iron and Steel Development Company, a 24-hour test at Ghadir Iron and Steel Company's direct reduction plant (Fig. 4.), and optimization of production at Ghayenat Steel's direct reduction plant. With over 70 control parameters in Midrex technology and intricate cause-and-effect relationships, achieving optimal control is challenging. Inspired by the Pareto principle (80/20 rule), the researcher aimed to identify the most influential control parameters in Midrex technology during the study. In the end, we successfully identified nine of the most influential control parameters in this technology. The most suitable guidelines for controlling the thermodynamic and kinetic conditions of Midrex plants were prepared by examining all the cause-and-effect relationships governing these nine parameters and considering the process flowchart of the plants. This compilation is presented in the form of KIPEX technical knowledge. It is worth mentioning that Midrex plants will have different process flowcharts depending on their nominal capacity and the type of product they can produce, which may be CDRI[1] – HDRI[2] or HBI[3]. Additionally, some equipment differences, such as the type of process gas compressors and cooling, will affect this technical knowledge.

Since KIPEX knowledge mainly focuses on nine out of the 70 control parameters of the Midrex technology, the mathematical model governing this knowledge for the optimal control of the production process will be very simple. This simplicity will facilitate its integration into the automation of levels 1 and 2 of Midrex direct reduction plants. Therefore, it can be claimed that control room operators using this knowledge will be able to predict and implement necessary process changes to optimize and stabilize the quantity and quality of the produced product from the moment the ore enters the furnace. This is an unprecedented or rarely seen practice in the current direct reduction industry worldwide.

The algorithm governing KIPEX technical knowledge has been designed to minimize additional load on capital equipment, such as reformers and process gas compressors, as much as possible. For example, using the algorithm will prevent the accumulation of carbon on reformer catalysts over time, extending the life of reformer catalysts and tubes beyond normal conditions.

In conclusion, it is worth mentioning that, depending on the capabilities and limitations of different direct reduction plants, this technical knowledge, through the optimal control of the thermodynamic and kinetic conditions of Midrex plant furnaces, can rapidly increase their production capacity by up to 30% compared to their nominal capacity, after its implementation in each plant.

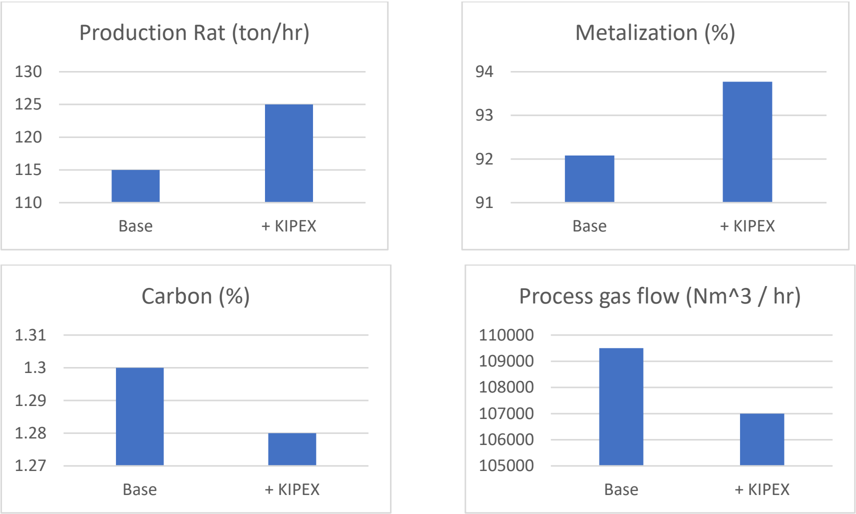


Fig. 4. Results of utilizing KIPEX knowledge in a 24-hour test at Ghadir Iron and Steel Company: (a) Production rate, (b) Metallization percent, (c) Carbon percent, (d) Process gas flow in Nm^3/hr.

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[1] Cold Direct Reduction Iron

[2] Hot Direct Reduction Iron

[3] Hot Briquetted Iron

4. Conclusions

Given that annual reports of Midrex plants contain valuable information, including equipment conditions, development plans, and their performance, such as the type of consumed ore, quantity and quality of the produced product, energy consumption, and energy carriers, a thorough examination and comparison of this information can lead to a comprehensive understanding of some technical principles and realities governing this technology. Fortunately, one of the most significant findings in this regard is the potential increase in the production capacity of these plants compared to their nominal capacity. In some leading plants worldwide, such as Qatar Steel, this has been achieved without the need for hardware changes. Shedding light on and informing managers and owners of direct reduction plants about these findings can redirect their focus toward software activities, including the implementation of KIPEX technical knowledge. Ultimately, this can create valuable opportunities for the growth of the steel industry.

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