A NEW COAL-BASED IRONMAKING PROCESS AND ITS REQUIREMENTS ON RAW MATERIALS

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SUMMARY

Theoretical and experimental work leading to the development of an environment-friendly ironmaking process at McMaster University will be review, and a new hearth furnace, Paired Straight Hearth (PSH) Furnace for ironmaking proposed.

Up to the present time, blast furnace has been the predominant process for ironmaking. In blast furnace, its productivity and fuel efficiency are result of using well prepared raw materials, i.e., coke and sinter or pellets. However, these preparatory steps also bring drawbacks to the system, such as the availability of coking coal and iron ore of high quality and environment impact of coking and sintering process.

A new ironmaking process, based on rotary hearth furnace and PSH furnace, will use low strength green agglomerates of iron ore and coal directly. Therefore it would have following advantages:

- The elimination of all pollutants and costs associated with coke production and iron ore sintering,
- High tolerance on certain impurities in iron ore, for example, alkalis and zinc contents
- The only properties of coal of concern are contents of volatile matter and ash.

The potential fuel efficiency and advantages in environment protection will also be discussed.

Key Words: Ore/Coal agglomerate, RHF, PSH Furnace

1. INTRODUCTION

The most important commercial process of ironmaking that converts iron ore and coal (natural gas) to metallic iron, remains to be blast furnace. It has the advantage of massive scale of production of liquid iron of consistent quality and relatively stable cost structure because it is based on coal. However, for any challenger to this giant reactor of well established status and dominant position in this field, one searches for its potential weak spots. In the past developers of rotary kilns, COREX and in last decade smelting reduction processes tried and failed. One must recognize that economical, political, social, and technological environment change with time so are the needs of steel industry. The tremendous force behind the changes today is globalization which means competition in the market will be tougher and regulations for environment protection will be more restrictive in the years to come.

The challenger can see that the efficient operation of iron blast furnace is based on excellent raw materials and very carefully prepared to its liking. Another important factor is the economy of size. It is capital intensive and has long time for the return of investment. These preparatory processes, sintering and cokemaking, have been considered by experts as well as the public to be much less than environment-friendly.

2. MAJOR ITEMS IN THE COST OF MAKING IRON

The costs under consideration are the operating cost and capital cost for blast furnace ironmaking in comparison with the new process which is based on metallizing iron oxide in a ore/coal composite in a hearth furnace heated by an oxidizing flame. The dominant items in operating cost are the prices of iron ore and coking coal, and the operating expenses for sinter plant and coke ovens. For the new hearth furnace, steps of agglomeration and coking are eliminated, thus, the economic benefit in both capital and operating costs would be crystal clear.

In order to have a smooth and productive blast furnace operation, the permeability for fluid flows throughout the furnace must be maintained. The control of the permeability depends on qualities of raw materials and burden distribution. The technology of sintering and coking are well developed and specifications for ore blends and coal blends are extensive. The operator of the new ironmaking process based on a hearth furnace would only pay for iron oxide in the ore and carbon and hydrogen in the coal because the only operational requirements are the size of ore and coal for agglomeration of the composite, pelletization or briquetting. The relaxation of quality requirement on iron ore and coal will enlarge the supply side of the market leading to a decrease in prices.

3. PROCESS FUNDAMENTALS

In blast furnace which is a gas-solid reactor, ore and coke are charged in separate layers. The job of heating and reducing iron ore is done by the gas passing by. Heat and mass transfers between gas flow and solids are mainly by convective mechanism. The overall rate of reactions of making iron is determined essentially by the rate of supply of reducing gas and heat, therefore, productive blast furnace must have good permeability, i.e., strong and well sized raw materials.

The ore/coal agglomerate is made to be chemically sufficient so that nothing (other than heat) needs to be supplied to the reaction site. The hearth floor moves in the furnace, not agglomerates. There is no induration step for these agglomerates so that they are mechanically weak and can not survive in blast furnace or any other type shaft furnaces. A hearth furnace is the most appropriate for the reduction of ore/coal agglomerates because it is good for heating things that sit on the floor. Heat is usually generated by burning CO (which is a product of iron ore reduction by carbon) and additional fuel above the bed of ore/coal agglomerates on the furnace floor. The rate of overall reaction for ironmaking is controlled by heat transfer by radiation mechanism. Heat transfer by radiation is highly sensitive to flame temperature that would offer the operator a direct and effective means to control the process.

4. THE MAKING OF GREEN BALLS

Good green balls (or agglomerates) of ore/coal mixture make the handling steps and reduction task easier. It should be uniform in composition, otherwise, one spot may be deficit in coal and the other has excess. The size of ore should be fine enough so that the overall reaction rate is not hindered by those large particles. The size of coal could be a little coarse than that of ore. Bryk and Lu[1] has reported effects of particle size of ore and coal on the reduction rate. At McMaster University, using coal up to about 20%wt., with 1% bentonite, good green balls have been made for magnetite concentrate, hematite concentrate, and several types waste oxides. Green balls are usually strong enough for our purpose, for example, the strength of dry green ball of iron ores is between 3 and 12 kg/pellet and strength of the pellet of waste oxide is between 10 to 40 kg/pellets. The wet green balls have no problem for transporting within the facilities.

5. ROTARY HEARTH FURNACES (RHF)

The most effective way to heat waste oxides generated in steel plants is through a reduction process to recycle metallic iron and to separate heavy metals (e.g,, zinc) by gasification during reduction and recapture them as oxides in dust collectors. In most cases, there are substantial amount of carbon in the waste oxides already. After adjusting chemical composition and moisture content, agglomeration can be done. Very little fundamental investigation was carried out because there is no unfamiliar reactions involved, at least to practicing engineers. Though a trial-and-error process, the rotary hearth furnace (RHF) became the winner because among all types of furnace RHF produces the least amount dust.

Current commercial Rotary Hearth Furnaces (RHF), see Fig. 1, are being used for both waste recycling and ironmaking. In INMETCO, at Ellwood City Pennsylvania, a RHF of 60,000 tonnes per year capacity was set up in 1978, for treating waste oxides from steel works[2,3]. In Iron Dynamics, Inc. (IDI), which formed in 1996 at Butler, Indiana, a RHF of 520,000 tonnes annual capacity was built. The RHF of IDI is followed by a Submerged Arc Furnace (SAF) for smelting of DRI to supply virgin iron for steelmaking [4].

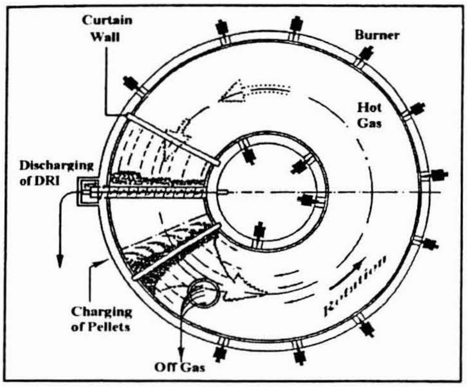


Fig. 1. The Top View of a RHF

In current practice of RHF, the pellets of iron ore or waste oxides and coal are placed on a solid hearth one to three layers deep[5]. As the hearth rotates, the pellets are heated to 1250 to 1350°C by means of fuel burners firing into the freeboard above the hearth. The DRI is discharged at approximately 1000°C and can be charged into an adjacent melter. A typical reported fuel consumption by another developer of similar process is listed in Table 1[5].

Table 1. Typical RHF Processes Inputs[5]

Item of input for per tonne of DRI	
Iron Oxide Feed (68%Fe)	1300 kg
Reductant Coal (75% Fixed Carbon)	380kg (11.4 GJ)
Burner Coal or Coal Equivalent (75% Fixed Carbon)	120kg (5.36 GJ)
Total fuel Consumption	16.8 GJ

As shown above, the total fuel consumption for producing per tonne of DRI is as high as 16.8 GJ which is even higher than that of blast furnace for per tonne of hot metal (13-14GJ/tonne-HM[6]). Besides poor energy efficiency, current RHF operation has other two major problems, i.e., lower degree metallization of DRI and lower furnace productivity in kg-DRI./m^2-hr. One must appreciate that the priority of the management of the plant of recycling waste oxides is inordinate. To make the process to do the job (making waste oxides to disappear) is far more important than energy efficiency, at least at present time.

As stated in last section, the contradictory requirement, i.e., an oxidizing flame for energy efficiency and reducing condition for the prevention of re-oxidation reduced iron, current practice represents a compromise. The solution of this problem will be presented later.

(1) Low Fuel Efficiency

The compromise in current practice is to keep gas chemical composition of the flame at CO/CO_2>2.0. The benefit is only in slowing down the re-oxidation of reduced iron but at tremendous expense of thermal efficiency as shown in Figure 2. If the furnace atmosphere has to be maintained at CO/CO_2=2.0, that means more than one half of heat of the fuel could not be delivered to the reduction area where energy is needed. This is the main reason why the fuel rate is so high in current commercial RHF. The ratio of heat liberated from different fuels under incomplete combustion comparing with completed combustion is illustrated in Figure 3.

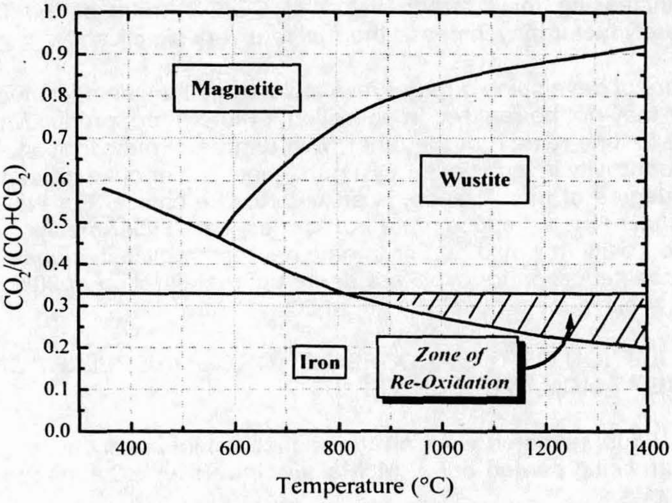


Fig. 2 The equilibrium atmospheres for FeO reduction

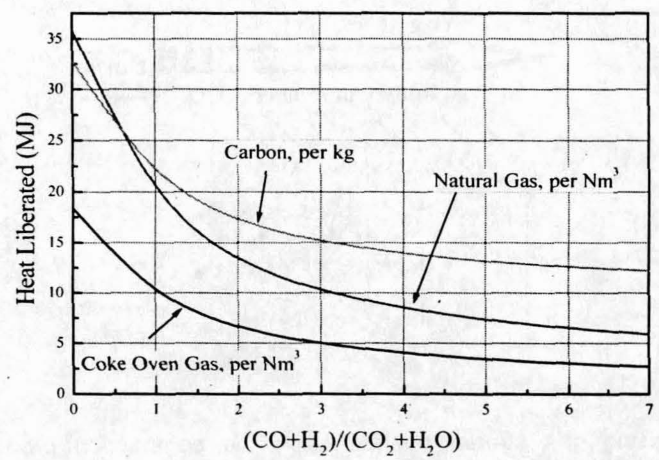


Fig. 3. The heat liberated from fuels in incomplete combustion

(2) Low Degree of Metallization of DRI and Low Productivity

Based on thermochemistry of the process, the iron oxides can be reduced by sufficient amount of carbon in the pellets without interference of surrounding atmosphere. In industry, it may be difficult to have burner generate a flame of the composition of CO/CO_2.>2.0 all the time and everywhere. That is reason why the metallization of DRI is varying between 40% and 85%. This problem may be partly solved by increasing the average value of CO/CO_2 ratio of the flue gas. This improved safety factor may increase the fuel rate very significantly.

It is the nature of developing a rather new technology that the designed capacity of a RHF may or may not be realized in operation. Furthermore, productivity in the same plant varies, for one reason or the other, with degree of metallization. The generally accepted productivity in terms of kg-DRI per square meter of hearth per hour, without referring to degree of metallization, is an unfortunate choice. For the same plant, it must take longer time to reduce more iron oxides, i.e., higher metallization will result in lower productivity. It would be fair to say that the practice in industry known to us for iron ore/coal reduction to result in a degree of metallization of 90%, it would be a challenge to achieve the productivity about 50kg-DRI/m^2-hr.

4. THE EVOLUTION OF THE PROCESS OF ORE/COAL PELLET ON A HEARTH FURNACE AT MCMASTER UNIVERSITY

Since early 1980s, research work on the reduction kinetics by heating the ore/coal composite has being carried out at McMaster University[7]. Overall reaction may be written as follows.

Iron oxide (solid) + Carbonaceous reductant (solid) → Iron (solid) + Gases

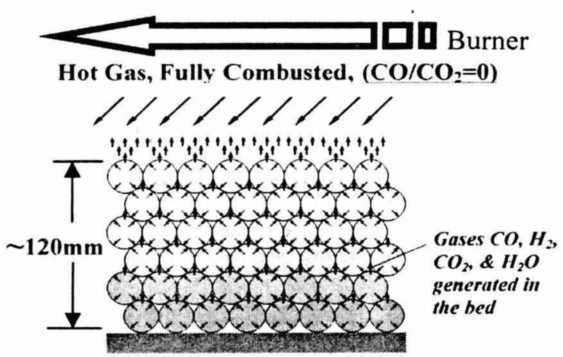


Fig. 4. The rising gas stream pushes back the combustion products which contains CO_2, H_2O and possibly O_2

For a tall bed under an fully oxidized flame (for energy efficiency) at a higher temperature, the situation may be represented by Figure 4.

The gases generated in the bed will rise to the top with a linear velocity depending on the rate of gas generation. This upward flow of reducing gas will hinder the penetration of gases from the flame to the top and the interior of the bed, i.e. resulting in re-oxidation of sponge iron. This picture suggests the possibility that a fully oxidised flame of very high temperature may be used to give a very fast heat transfer without re-oxidation of metallic iron, provided the protective gas flow is maintained above certain linear velocities over a certain period of reaction time. The conditions for a sustainable gas flow are high temperatures, carbonaceous reductant containing sufficient volatile matter, and a tall enough bed simultaneously to make the heat transfer rate across the layers of reduced agglomerates adequate and to supply the gas stream over a long period of time. Based on this idea and early experimental data, a patent application was made.

5. THE CURRENT EFFORT AT MCMASTER UNIVERSITY

In order to develop this process one step further, financial assistance from American Iron and Steel Institute (AISI) and U S Government was sought and received. An AISI sponsored project for the duration 1999 to 2001 is in progress. The project has been very successful but the confidentiality has not been lifted yet. The following general information has made public by AISI in the past.

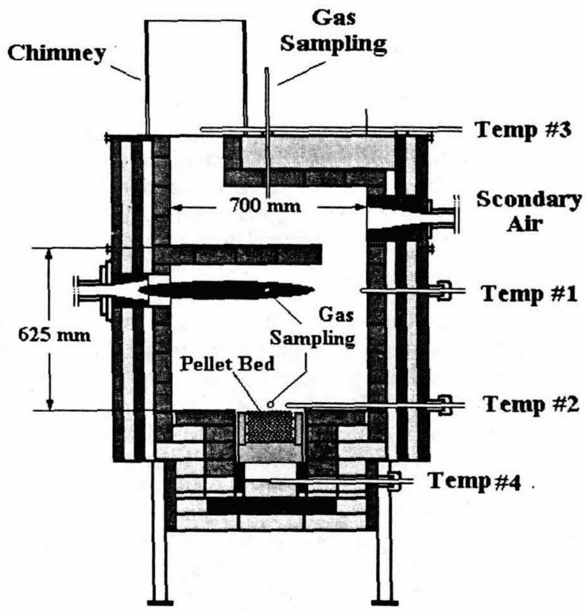


Fig. 5 The Scheme of Gas-Fired Furnace at McMaster University

A specially designed, natural Gas-Fired Furnace (Figure 5), with heat size of 6 to 7 kilograms of green balls (dried) in a bed of 120 mm height, was operated with fully combusted flame to process mainly iron ores. The results were judged to be very good. The contractual work sponsored by AISI has indicated that a tall bed of ore/coal pellet (including waste oxides/coal pellets), e.g.120mm, under a fully oxidized flame of 1600 to 1650°C may lead to a stable and efficient operation in the production of DRI of high density and high level of metallization. Five weeks experimentation in a pilot plant in Italy in the summer of 2000 has confirmed that the laboratory success achieved at McMaster University can be repeated on a significantly larger scale in an industrial setting. It also demonstrated that this technology can be used to process waste oxides generated in carbon steel plants. The typical results of ore/coal pellet reduction and waste oxides recycling are listed in Table 3. It is easier to process iron ores than waste oxides from steel plants, because of more consistent properties of the former.

Table 3 The Typical Results of the Reduction of Tall Bed of Pellets in Gas Fired Furnace

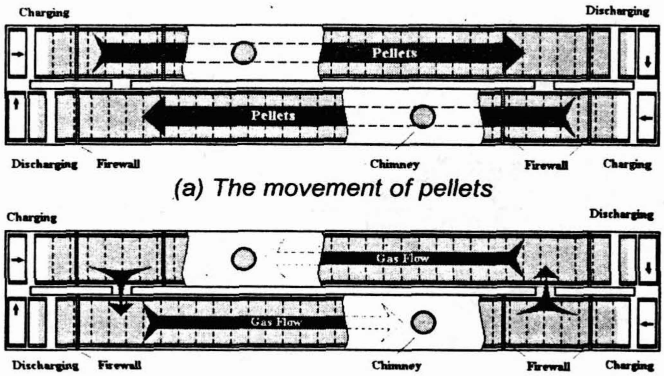
Degree of Metallization:	>93%
Density of DRI	2~6 g/cm^2
Productivity (DRI)	>100 kg/m^2.hr
Zinc Removal	95~99%
Lead Removal	~100%

6. A NEW HEARTH FURNACE FOR THE REDUCTION OF TALL BED OF IRON ORE/COAL PELLETS

The potential advantages of using high process temperature and tall bed in achieving operational efficiency and product quality can be realized in a hearth furnace, but not necessarily a RHF. In current practice, a screw discharger is used to remove DRI off RHF from the outer edge of hearth in the radial direction, see Figure 1. It presents two problems (i) the flights have to be cooled (ii) no retaining wall for tall bed can be built.

As shown in Figure 4, the kinetics of the system is independent of the shape of neither hearth nor its movement. The problems related to discharger of RHF may be avoided by the design of a new furnace. A new type and patented hearth furnace, The Paired Straight Hearth (PSH) Furnace[8,9], has been proposed, which contains two interrelated straight hearth furnaces. Each of the straight hearth furnaces is made up of detachable pallets, similar to that in sintering machines, and arranged side by side, see Figure 6. The pallet is lined with refractory materials.

After a predetermined time of processing, DRI on a pallet passes through a firewall to reach the discharging end. It may be discharged by a tilt/dump method from the pallets to the receiving container below. The emptied pallet is moved to be attached to the charging end of the adjacent furnace to receive the pellets, as shown in Figure 6. There is no need to use water sealing to isolate the combustion chamber because the side wall is extended all the way down to the ground.



(a) The movement of pellets

(b) The movement of gas

Fig. 6 The top view of a PSH furnace and the movements of solids and gas

7. HEAT AND MASS BALANCE OF THE PROCESS OF PSH FURNACE

In an earlier report [10] heat and mass balances, with and without melting steps, has been attempted. A series of heat and mass balance of the tall bed process has been computed and with the benefit of improved information about reaction products will be discussed briefly in this section. The following is conditions for computations and an examples of computation results with relevant raw materials.

Table 5. Raw Materials

- Taconite compositions (wt.%)

TFe	FeO	SiO_2	CaO	Al_2O_3	MgO	S	P
66.06	30.28	4.09	0.27	1.11	0.62	0.02	0.02

- Compositions of Brazilian Hematite (wt.%)

TFe	FeO	SiO_2	Al_2O_3	P
66.41	4.60	0.78	1.55	0.046

- Coal Composition (wt.%)

C total	C fixed	Volatile Matter	Ash	S
82.00	60.81	34.11	5.08	0.85

Table 6. Products Composition

- DRI Composition (wt.%)

TFe	MFe	FeO	C	SiO_2	Al_2O_3	CaO	MgO	Other Oxides	Degree of Metallization (%)
83.4	79.3	5.4	2.5	5.9	1.8	0.35	0.78	3.97	95.0

- Exit Gas Composition (v.%)

CO_2	H_2O	N_2	S_2
23.76	10.86	65.37	0.01

Table 7. Mass Balance

Input		Output	
	kg		Kg
Taconite	1261.8	DRI	1000.0
Coal*	324.8	Off Gas	2599.0
Preheated Air	2012.4		1895.4 (Nm^3)
	1565.0 (Nm^3)		
Total	3599.0	Total	3599.0

* This coal requirement includes the amount of coal for the residual carbon in DRI. It would be reduced to 305kg coal per tonne DRI if without considering of the residual carbon.

Table 8. Heat Balance

Input	MJ	%	Output	MJ	%
$C + O_2 \rightarrow CO$	140.6	1.42	Endothermic Direct Reductions	2975.5	30.09
$CO + O_2 \rightarrow CO_2$	5703.2	57.66	Decomposition of Coal	326.4	3.30
$H_2 + O_2 \rightarrow H_2O$	2225.4	22.50	Sensible Heat of DRI	1108.9	11.21
Preheated Air at 850°C	1821.8	18.42	Sensible Heat of Gas	4026.2	40.70
			Heat Loss	1454.0	14.70
Total	9891.0	100.00	Total	9891.0	100.00

The influences of ore type, preheating air, degree of metallization of DRI, and the use of oxygen instead of air on coal rate and heat requirement are illustrated in Figures 7.

In the case of air with oxygen enrichment is used instead of preheating, the amount required of coal and oxygen addition is shown in Figure 8.

8. DISCUSSIONS

In this article the merits of this new process are compared with blast furnace for its advantages in the elimination of sintering and coking steps and the enlargements of supply of ore and coal due to relaxed requirement on qualities. How it must be pointed out that this process, making DRI in PSH Furnace, produce solid product at 1400°C, not liquid hot metal. The use of a melter is needed for melting, carburization and slag-metal refining to produce hot metal of comparable quality of that from blast furnace. On this subject see the article by Gou and Lu[10]

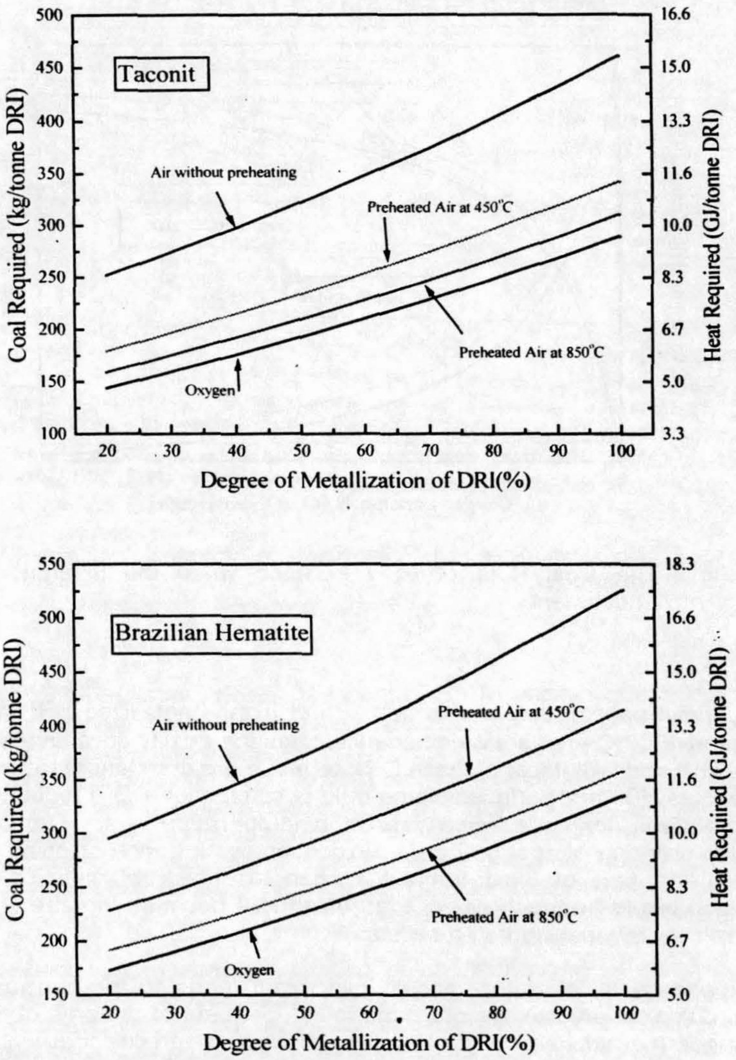


Fig. 7 The Coal and Heat Required for PSH Furnace Process to Produce DRI of different Metallization using Taconite and Brazilian hematite under different operational conditions

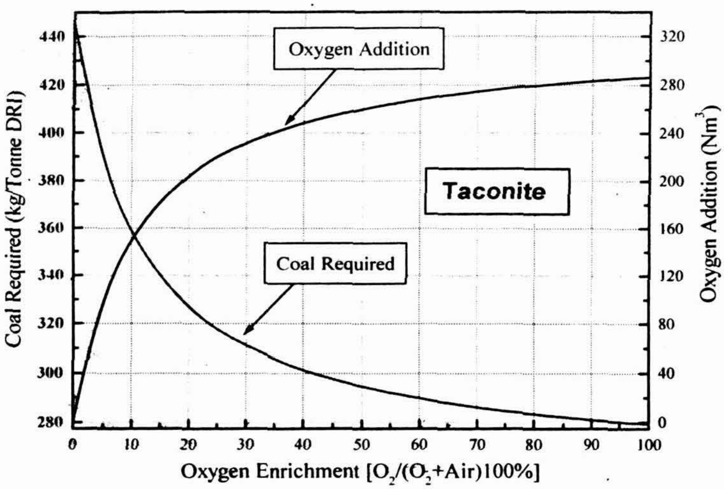


Fig. 8. The Coal Rate of PSH Furnace when the different Oxygen Enrichment

The potential applications of this dense and highly metallized DRI made by PSH Furnace at 1500°C are very wide because it has the quality advantages of both shaft furnace DRI and HBI. Most of these DRI we made are of a density to sink in a molten slag pool, as HBI, and surface/volume ratio of conventional DRI for fast melting. Due to the relatively long residence time at a temperature near 1500°C to result in extensive sintering of sponge iron, no oxidation in air during shipping or storage is expected. As part of blast furnace burden, the task of charging and burden distribution would be much easier than using HBI because the size is in the same range as conventional indurated pellets.

Our experience in laboratory and in pilot plant leads to the conclusion that the thermal chemical process we observed is independent of the area of floor because all changes thermochemically take place along the vertical direction. It is a one-dimensional system so that there is no risk, in principle, in scale up as far as chemical reactions and heat transfer are concerned. However, we are looking forward to establishing the range of energy efficiency in a demonstration plant. To our best knowledge, there is no creditable way to calculate it based data collected in much smaller unit.

9. CONCLUSION

(1) A new ironmaking process based on heating ore/coal agglomerates in a tall bed placed on the floor of a hearth furnace is being developed for the production of virgin iron as well as recycling of waste oxides.

(2) In comparison with blast furnace, the elimination of sinter plant and coke ovens and the enlargement of the supply of raw materials will contribute significantly to the economy of ironmaking. This new process is very much environment-friendly because less coal is used per tonne of iron produced, and coal is used in a furnace of oxidizing atmosphere and negative pressure.

(3) In comparison with conventional rotary hearth furnace, the new process has higher productivity, lower fuel rate, DRI of better qualities (in degree of metallization, density, strength, resistance to re-oxidation, and having higher sensible energy for melting in the next step). Operational difficulties due to the use of the screw discharger in RHF intensify at higher temperature on taller bed. RHF may be replaced by PSH Furnace which has tilt/dump discharging mechanism.

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