LOW COST HOT METAL: THE FUTURE OF BLAST FURNACE IRON–MAKING[1]

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Abstract

The presentation addresses: Continuous operation at high coal injection rates (> 200 kg/tHM), low coke rates (< 300 kg/tHM) and high productivity is possible. It will be shown that application of increased oxygen enrichment of the wind compensates for adverse effects of high PCI levels (notably permeability and presence of unburnt char in top gas). Application of higher oxygen enrichment leads to a top gas product with a higher calorific value, which allows for higher value applications of top gas (e.g. less natural gas enrichment requirements for firing the hot blast stoves, power generation, etc.). Utilization of the "coal gasification capabilities" of the blast furnace allows for an operational area, where the value of the top gas increases from 10% of the total product value (hot metal and gas) to more than 25%. Blast furnace lining designs capable of achieving long campaigns while maintaining a stable inner profile allowing for stable burden descent, which is essential in high productivity blast furnace iron–making.

Keywords: Blast furnace; Fuel injection; Ore fine injection; Ironmaking.

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1 INTRODUCTION

The development of blast furnace iron–making process in the years to come will be determined by the following.

a) The development of hot metal costs. If we take the costs of the ore burden as given, the hot metal costs are mainly determined by the consumption of reductants (coke and coal) as well as the productivity. The process will develop to high pulverized coal injection (PCI) rates (> 230 kg/tHM) and high productivity (> 3 t/m^3WV/24hrs).

b) The reduction of CO_2 footprint. CO_2 footprint can be reduced by utilizing more efficient available resources, i.e. decrease of energy losses, increase of efficiency of top gas calorific value utilization and potential use of renewable resources.

The blast furnace will remain the successful process for hot metal production for the coming thirty years for the following reasons:

- The progress of alternative iron–making processes is slow. Kepplinger(1) reviewed the actual state of smelting–reduction processes. His conclusion was, that only the Corex–Finex process and possible the Hismelt process have reached the commercial state.
  Investment in alternative processes will be limited because of elevated business risk compared to the blast furnace.
- Hot metal costs of existing blast furnaces, where capital has already been spent and depreciated, has to be compared with new equipment, where the capital still has to be committed.
- There is a large unused iron–making capacity in almost each blast furnace. Blast furnace productivity can be improved, for example, by using more oxygen enrichment.

The present paper is directed towards the potential benefits of application of hot blast oxygen enrichment to a level beyond the minimum requirements of high coal injection rates and the future equipment requirements.

2 PROCESS: PCI RATES AND OXYGEN ENRICHMENT RATES

2.1 Present Situation

Figure 1 shows the inputs and outputs of a blast furnace. We refer to Table 1 showing a typical example of the consumption figures (calculated with a mass and heat balance model) and operational expenditures (OPEX) per ton hot metal. OPEX is estimated for a 10.000 t/d blast furnace, equipped with PCI and modern blast temperatures, top pressure and pellet burden. Price basis is 2007. The top gas is valued at 70% of natural gas market price. Oxygen price is integral cost consisting of a fixed and variable component.

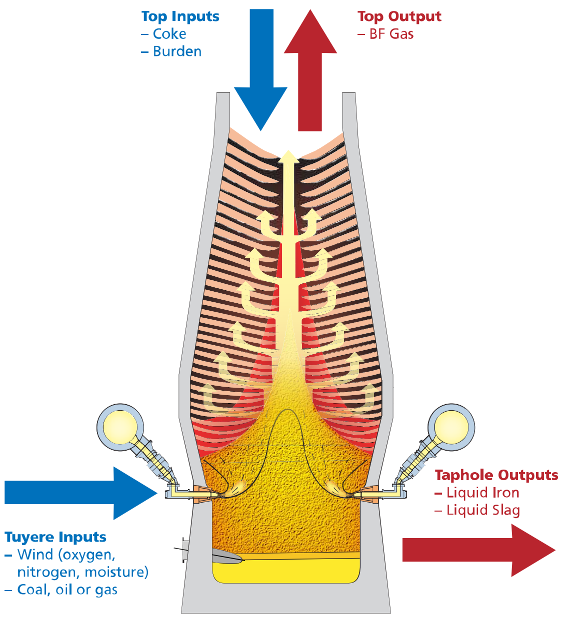

Figure 1. Inputs and outputs in a blast furnace.

Table 1. Major inputs, outputs and OPEX per ton hot metal, typical, prices in US$ (2007)

Major input per ton hot metal

		A	B
Pellets	kg/t	1.600	1.600
Coke	kg/t	334	267
PCI	kg/t	160	240
Oxygen in wind	%	24,2	33,4
Oxygen from plant	m^3 STP/t	42	122
Net make gas after stoves	GJ/t	3,4	4,2
Production	t/d	10.000	10.000
Top gas	m^3 STP/t	1.502	1.292
Top gas temperature	℃	156	101
Top gas calorific value	kJ/m^3 STP	3.426	4.281

OPEX per ton hot metal

Unit	US$/unit	A	B
t	94	150	150
t	196	66	52
t	90	14	22
1000 m^3 STP	70	3	9
GJ	–6,16	–21	–26
Other OPEX		31	31
Total OPEX (US$)		**243**	**238**

A large part of the OPEX are the costs of the ore. For most companies, the ore (sinter fines, pellets or lump ore) are purchased from external suppliers. The prices are mainly determined by market conditions and cannot be easily influenced by the blast furnace operator. The operator has more control on the fuel (reductant) side of the OPEX. Coal is cheaper than coke and the top gas has a cash value, which depends on local gas/energy balance. In Table 1 we present scenario “A” with a coal injection rate of 160 kg/tHM, minimum oxygen enrichment in wind and scenario “B” with PCI at 240 kg/tHM and high oxygen enrichment. The higher coal injection leads to a cost decrease of about 5 US$/tHM.

Many companies have therefore tried and reached low coke rates, high PCI operation.[1-6] The general conclusion is that coke rates below 300 kg/tHM were reached at many companies, among others BaoSteel, POSCO, Corus, ArcelorMittal and CSN. The problems mentioned to maintain the low coke rates, besides equipment[1,7] are:

- It is difficult to maintain simultaneously high productivity and low coke rates, due to the decreased permeability of the furnace and the increased gas production.
- Occasionally unburnt char is observed in the top gas.

- Oxygen enrichment of the hot blast should be kept at the lowest possible level because of costs.

The decrease in permeability of the furnace is in part caused by the replacement of (well permeable) coke by (poorly permeable) ore burden and in part by the effect of PCI rate on top gas temperature. The latter effect is not everywhere recognized. It can be minimized by application of low–volatile injection coals and by maximizing oxygen injection rates. We have not generally observed unburnt char in the top gas if top gas temperatures are low (100–130 ℃). Finally: oxygen costs in the range of 60–90 US$ per 1000 m³ STP, which is about 4 times oxygen coming from a blower. For 1 ton hot metal about 250 m³ STP oxygen is required. But in evaluating the application of high oxygen enrichment rates, the higher productivity as well as the higher energy content per ton and calorific value of the top gas have to be taken into account.

2.2 Future PCI Rates and Oxygen Enrichment Rates

We have come to the working hypothesis, that coal gasification at the present levels of injection (up to 250 kg/tHM) is not an issue. This is based on the following additional observations.

- There is no evidence, that low coke rates, high PCI injection rates are very much limited by coal type. It is well known that high volatile coals gasify much easier than low volatile coals; however BaoSteel reached very low coke rates with low volatile coals.
- There is no evidence on limitations provided by PCI equipment. Measures to improve coal gasification (like oxy–lances, coal heating, finer grinding) have not resulted in higher injection levels than without these measures. The highest, continuous coal injection rates have been maintained at the Corus IJmuiden works, where coal is injected in a single straight lance into the tuyere.
- There is no evidence of limitations provided by thermodynamics or kinetics of gasification process. Coal gasification is not an issue for industrial entrained–flow coal gasifiers, while in these gasifiers, flame temperature is lower (1250–1500 ℃) and residence time shorter (10 ms). Note that the flame temperature of coal and oxygen reacting to carbon monoxide and hydrogen is about 2000 ℃. For this reason coal gasifiers do not use pure oxygen.

This allows to conclude that blast furnace capability to gasify coals is currently underutilized and has not reached it limits. It is difficult to predict exact numbers (which will be different for each furnace), however coal injection level of 250 kg/tHM does not seem to be a limit and rates up to, and even above, 300 kg/tHM should be achievable.

2.2.1 How can high productivity and low coke rates simultaneously be maintained?

High productivity and low coke rates can be simultaneously maintained when using higher oxygen enrichment rates. How much oxygen is required? In Figure 2 a typical example of the mass and heat balance of a blast furnace is shown. There is a minimum oxygen enrichment rate in order to reach a minimum flame temperature and a maximum oxygen enrichment rate corresponding to a minimum top gas temperature. The minimum top gas temperature of about 100–110 °C is required to drive all moisture from the charged burden and coke. The highest productivity is reached, when maximizing oxygen enrichment. In other words, if the nitrogen throughput through the furnace is minimized. The balances have to be calculated for every furnace based on the local conditions with respect to burden quality and coal quality.

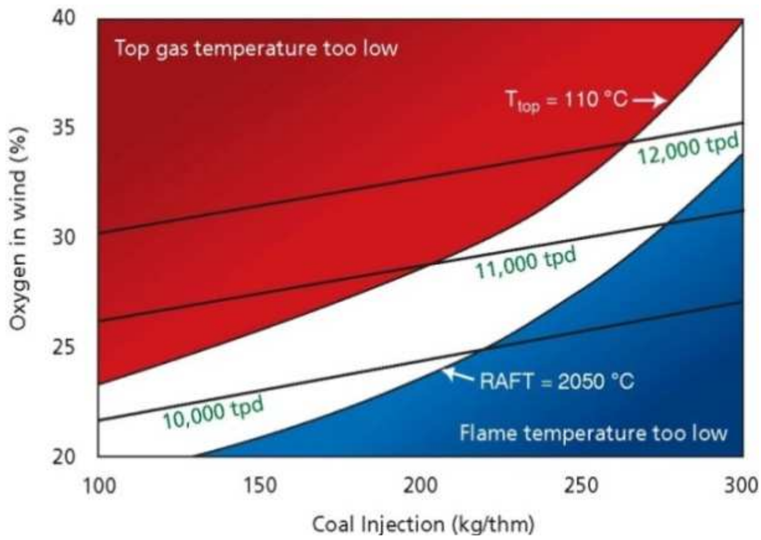

Figure 2. Limiting factors affecting raceway conditions with Pulverized Coal Injection (RAFT = Raceway Adiabatic Flame Temperature).

2.2.2 Present and future process conditions compared

In Table 2 the present and future process conditions are summarized. This will lead to more demanding requirements for the design. Not only will the heat load in tuyere area and bosh increase, also the hearth will have to cope with higher production levels. The demanding character of the future process conditions forms the basis for our discussion requirements with respect to the PCI and oxygen rates, the blast furnace proper, and the hot blast system.

Table 2. Outlook iron–making technology

	2009	2015	2020
Max. Productivity, t/m³WV/24hrs	2,7–2,9	2,9–3,1	3,1–3,5
Blast Temperature, ℃	1050–1250	750–1050	600–750
PCI, kg/tHM	120–200	220–260	300+
Coke Rate, kg/tHM	300–360	240–270	220–260
Blast Oxygen, %	21–29	~ 35	40– – 60
Top Gas Calorific Value, kJ/m³ STP	3100–3900	4500–4900	> 5900
Export Power MW MWh / tHM	25–50 ~0.2	125–160 ~0.5	200–250 ~0.8

3 EQUIPMENT

3.1 Oxygen and PCI Rates

In Table 3 a typical example of the changes in required PCI rates and oxygen rates is shown. With increasing oxygen enrichment levels in the hot blast, the amount of oxygen coming from the Air Separation Unit (ASU) increases and wind requirements decrease. As a consequence, modern blast furnaces will be equipped with a dedicated ASU, where oxygen is made with a purity of 95–98%.

Table 3. Design requirements (250 m³ STP O_2 per ton hot metal)

		Present	Future		
PCI	kg/tHM	200	300		
Oxygen in hot blast	%	25–30%	35–40%		
Oxygen % in hot blast		25%	30%	35%	40%
Air via blower	m³ STP/tHM	946	734	581	471
Oxygen from ASU	m³ STP/tHM	53	99	131	155

3.2 Blast Furnace Proper

3.2.1 Bosh and stack

It is of paramount importance that the profile of the bosh, belly and stack is maintained during the entire campaign as any degradation will immediately have a negative influence on low–cost hot metal production requirements.[8,9] Hence, bosh, belly and stack designs must be robust and strong.

The authors evaluate the ‘integrated lining design’ as one system: this system includes mechanical (shell and cooling members), refractory and process engineering (cooling system) components.

History has proven that high–efficiency designs using highly–conductivity materials are required to secure low shell temperatures and long campaign life based on the premise that lining protection is achieved by a solidified layer in the bosh, belly and lower stack. Under the conditions of future iron–making (high oxygen, high PCI rates) the heat exposure to bosh and tuyere belt will increase.

Copper stave coolers have a high cooling–efficiency but cannot survive all process conditions. Exposing conventional copper stave coolers to fluctuating high–temperature process condition can result in leaking cooling channels due to expansion issues (cracking of pipes). It is also observed that copper stave cooler designs have a limited ‘anchoring’ performance for a protective layer and this could result in exposure of the copper stave coolers to the abrasive and erosive descending burden and ascending of gases. Copper has a limited resistance against abrasion and erosion and wear of the copper ribs will catalyze further loss of anchoring functionality. These failures prohibit low–cost hot metal production.

State–of–the–Art copper plate cooler design includes high–conductive graphite refractory in the bosh, belly, lower and middle stack. This graphite provides thermal protection to the embedded SiC refractory courses in the belly and stack. The SiC provides protection against abrasion and erosion and this design provides a synthesis of thermal and mechanical components.[9]

In addition, copper plate coolers are always required at the transition of tuyere zone and lower bosh, and lower bosh itself to permit high coal injection rates and to protect the tuyere–coolers. The high coal injection levels and oxygen enrichment levels which we foresee for the future lead to very high flame temperatures at and above the tuyere ring. This is caused by the fast conversion of coal to CO_2.

3.2.2 Bottom and hearth

The bottom and hearth are critical in determining the campaign life. It will be exposed to higher loadings if the productivity increases due to the application of higher PCI and oxygen enrichment rates. In addition, we believe that the voidage of the dead–

man reduces at higher PCI rates unless the coke strength is increased. Various bottom and hearth designs have been developed and installed and campaigns > 25 years have been recorded, albeit at low to moderate productivity rates.
The bottom and hearth are exposed to a variety of wear chemical/thermal and mechanical wear–mechanisms and these tend to catalyze each other. It is important to utilize (super) micro–pore carbonaceous refractory materials and scientific experiments must be utilized to benchmark the materials. An example of corrosion testing is provided in Figure 3, where different types of refractory are exposed to iron at 1550℃ and 3% C. Many recent research activities have focused on modeling of hearth liquid flows in order to understand operational conditions and the impact thereof on the hearth isotherms. It is believed that the structural integrity of the bottom and hearth must be secured, which requires a sound design analysis. The structural integrity of the hearth can have an immediate impact on the lining and shell life if not properly addressed. New materials, such as (ultra–) micro–pore carbons and high–grade ceramics, will impose higher loadings to the shell due to higher modulus of elasticity and coefficient of thermal expansion and require customized models. It is therefore important to perform computer models of dynamic thermo–mechanical multi–physics, and compare the results against field testing in order to develop advanced designs. Good hearth designs consider field observations and experiments and have resulted in these trends:

- Under–hearth water cooling
- Hearth shell jacket cooling
- Ceramic under–hearth course(s) / Ceramic Cup
- Copper stave coolers / Graphite against the shell
- Micro–pore carbon Semi–graphite
- Increased sump depth
- Increased hearth volume

Figure 3. Corrosion Performance.

3.2.3 The taphole

The taphole is the one of the most challenging blast furnace components as it is exposed to an extremely violent environment: operations and process conditions are discontinuous at high temperature and pressure (difference) and contains chemical / corrosive / erosive mechanisms. Low cost hot metal operations will increase the loading conditions as the productivity will increase. This means that the taphole performance design must always be monitored and evaluated and 'lessons learned' must be identified and implemented in the design.

Taphole cooling mechanisms and refractory components include:

Cast Iron Staves	Alumina / SiC ceramics
Jacket Cooling	Carbon
Spray Cooling	Hot Pressed Small Bricks
Copper Stave Cooling	(Ultra–) Micro–pore carbon
	(Ultra–) Micro–pore Semi–graphite
	Graphite

We continue our pursuit of the ultimate taphole design and believe that a combination of double densified graphite against the shell, external jacket cooling, internal micropore carbon / semi–graphite and a castable core provides maximum redundancy and minimizes operational flaws such as gas–leakage. Alternatively, copper stave coolers could be considered at the taphole. Reference is made to Figure 4. These designs provide significant value as they will permit stable operations at high productivity levels.

Figure 4. Taphole copper stave coolers.

3.2.4 Tuyeres, tuyere stocks and injection lances

Since we expect hot blast flow to decrease as well as hot blast temperature, the tuyere diameter has to decrease in order to maintain an appropriate wind speed. In addition to the sizing, the injection system will have to be upgraded for more injecting possibilities, e.g two lances per tuyere for coal and possibly an additional injection capability for cold oxygen. In addition to this, the thermal load to the tuyere will probably increase since close to the tuyere a substantial amount of CO_2 is generated, which is later converted to CO.

Hot blast flow distribution among tuyeres is not even and not constant in time.(11,12) The authors learned that the variability of hot blast flow is much larger than the variability of injected coal amount. To our knowledge there does not yet exist a measurement system that gives reliable hot blast flow in each tuyere stock. Therefore, the design of injection system should be based on self–regulating system, which will make coal flow dependant on the same factors as the hot blast flow, which can be provided by pressure–drop based systems.

3.2.5 Operational safety

High oxygen rates require some measures in the hot blast system e.g. use of lubricants suitable for the purpose and easy access for leak control of the hot blast system. Operational warning systems with respect to blockage of tuyeres and breakage of lances have to be put in place.

3.3 Hot Blast System

Internal, external and dome burner hot blast stoves are installed world–wide and provided by various designers. All ‘conventional’ hot blast systems include comparable components such as checkers and checker support, ceramic burner and external waste gas heat recovery systems. Historical developments have resulted in refractory design improvements, high–efficiency checkers and improved coatings against inter–crystalline stress corrosion. This permits long campaigns > 30 years and improved efficiency to–date.

Running developments focus on lower CAPEX/OPEX, reduced emissions (CO, CO_2), reduction of enrichment gas consumption and improved performance of waste gas heat recovery systems. These are ‘intrinsic’ developments driven by the engineers to provide competitive solutions.

The future of hot blast systems, however, will mainly be driven by iron–making process technology developments. These will target reduction of costs related to Energy & Environment. This can be accomplished by lower coke rate, higher fuel injection (pulverized coal) rate, increased (calorific) value of top gas, higher oxygen enrichment, lower hot blast temperature and lower CO_2 emissions.

We envision significant changes to conventional hot blast systems due to changes to iron–making process technology, described in the Introduction. These includes industrial changes towards lower hot blast temperatures and lower hot blast volume in combination to higher PCI and oxygen enrichment rates. This will provide advantages – reduction of CO_2, increase of energy utilization – if synergies are accomplished with power–generation.

In the near future, we will probably face reduction of the stoves’ capacity and maximum design temperatures, wider application of alumina refractory instead of today’s more advanced silica, wider temperature range by means of increased cold blast mixing capacity. These changes will be backed–up with increased attention to safety issues related to elevated oxygen levels.

Ultimately, the nature of the hot blast system will change and continuous heat exchangers could be considered for lower ‘hot’ blast temperatures and the capacity of the turbo–blower can be reduced. These changes will significantly contribute to low cost hot metal. The blower of the Air Separation Unit can be designed into the hot blast system as a back–up for blower breakdown, blower repair and/or all coke operation.

4 CONCLUSIONS

In the coming 10 to 20 years we expect the blast furnaces to develop from a single product (hot metal) to a two products (hot metal and gas) production facility. Therefore, the blast furnaces will be operated at higher coal injection rates as well as higher oxygen enrichment rates. A number of measures have to be put in place like thermal control schedules for the blast furnace operator as well as measures and checks for operational safety. But in doing so, the blast furnace will gasify more coal, use less coke per ton hot metal and can be operated at higher productivities. As a consequence of the changes in blast furnace process we envision the following adjustments in blast furnace equipment .

- The bosh will have to be changed to high density cooling plates; the stack will be designed using cooling plates in case of relatively poor raw material quality, and designed with staves in case good quality raw materials are used.

- Oxygen supply to the furnace to the blast furnace by dedicated oxygen plants; the capacity will be above 125 m^3 STP/tHM.
- PCI rates to be used in the blast furnace have to be designed for 300 kg/tHM.
- Optimized circumferential symmetry of blast and coal injection have to be designed, based on self–regulating system, which will make coal flow dependant on the same factors as the hot blast flow.
- Tuyere design will have to be adjusted in size to withstand higher heat load exposure and to facilitate multiple injectants (coal and cold oxygen) .
- Hot blast stoves will be developed into systems working at lower hot blast temperatures and potentially developed into continuous heat exchangers.

REFERENCES

1 NAITO, M. Development of iron–making technology, *NSC technical report*, v. 94, 2–15, 2006.

2 CARPENTER, A. Use of PCI in blast furnaces IEA Clean Coal Center, ISBN 92–9029–432–9, 2006.

3 IRONS, G. (ed) The challenges of coal injection in today's blast furnaces, *36th McMaster University Symposium on Iron and Steelmaking*, 2008.

4 ZHU RENLIANG; GUA KEZHONG Characteristic of 200 kg/tHM PCI and low coke rate of blast furnace in Baosteel, *Iron–making conference proceedings 2000*, p. 321, 2000.

5 SOUZA DE MONSORES, A.J.; MEDRADO DA SILVA, AGENOR; FERNANDES, H.A.; NOBLAT, S.J.X.; NOBREGA DE AGUIAR, F. Operation Of The Blast Furnace N.3 CSN With High Rates Of Coal Injection, *3rd International Meeting on Iron–making and the 2nd International Symposium on Iron Ore, ABM*, 2008.

6 BERGSMA, D.; KIEFTENBELD, B; BOL, L. Ramping up PCI production, *36th McMaster University Symposium on iron and Steelmaking*, 2008.

7 KEPPLINGER, W.P. Actual state of smelting–reduction processes in iron–making, *Stahl und Eisen*, v. 129, p. 7–43, 2009.

8 NOGAMI, H.; YAGI, J–I.; SAMPAIO, R.S. Exergy analysis of charcoal charging operation of blast furnace, *ISIJ international*, v. 44, 10, p. 1646–1652, 2004.

9 ICHIDA M.; TAKAO M.; MORIZANE Y.; NAKAYAMA T.; ANAN K.; KAKIUCHI K.; YAMADA I. Inner Profile and Burden Descent Behavior in the Blast Furnace, *Nippon Steel Technical Report*, v. 94, 2006.

10 VAN LAAR, R.J.; VAN OUDENALLEN, R.G. Advanced Blast Furnace Bosh and Stack Systems, AISTech 2009.

11 VAN OUDENALLEN, R.G.; VERBRAAK, P.; GEERDES, H.A.M.; KLAASSEN, M.G.O. Blast Furnace Circumferential Process Symmetry – The Effect Of Flow Distribution In Hot Blast Systems, AISTech 2009MALDONADO, D.; AUSTIN, P.R.; ZULLI, P. Modeling coal combustion in an iron–making blast furnace raceway, *Iron and Steel Technology*, March 2009, p. 50, 2009.

12 GEERDES, M.; TOXOPEUS, H.; VAN DER VLIET, C. Modern Blast Furnace Iron–making, IOSpress, Netherlands, ISBN 978–1–60750–040–7, 2009.

13 HIGMAN, C.; VAN DER BURGT, M. Gasification, Elsevier GPP, ISBN978–0–750608528–3, 2008.