The future of BF ironmaking: lowering hot metal costs with innovative processes

The BF will remain the dominant ironmaking route for the next 50 years. Options to further reduce BF iron costs and improve productivity include producing and utilising higher calorific BF top gas for greater efficiency combined-cycle power generation, flux injection to modify slag fluidity and increase furnace permeability, and use of pre-reduced iron units as part of the charge or via injection.

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Blast furnace operators continually strive to reduce costs and improve productivity. Over the past 10-20 years cost reduction has been helped by an increase in coal injection rates and increased productivity through oxygen enrichment of the blast. Best in class furnaces now reach productivities well above 3tHM/m^3 working volume per day and typically operate at coke rates between 260 and 300kg/tHM.

We have investigated possibilities for further reduction of hot metal cost. First we analysed the various processes available as alternatives to blast furnace ironmaking. Our conclusion is that the blast furnace will remain the process of choice for hot metal production in the coming 50 years for the following reasons:

- Alternative ironmaking route development is slow
- Hot metal costs from existing blast furnaces, where capital has already been spent, has to be compared with new equipment where the capital still has to be committed
- There remains untapped blast furnace ironmaking productivity capacity such as by using more oxygen enrichment

This conclusion is made while still taking into account that the discussions on CO_2 footprints and coking coal reserves favour development of alternative ironmaking processes. This may in fact sound the final death knell for the blast furnace ironmaking route in the longer term, but for the timespan stated here, the blast furnace is expected to remain unchallenged as the lowest cost producer.

Our focus, therefore, is on cost reduction of hot metal produced via the blast furnace route. Besides the self-evident value of even higher levels of coal injection and lower coke rates we have found three areas for future cost reduction. These are:

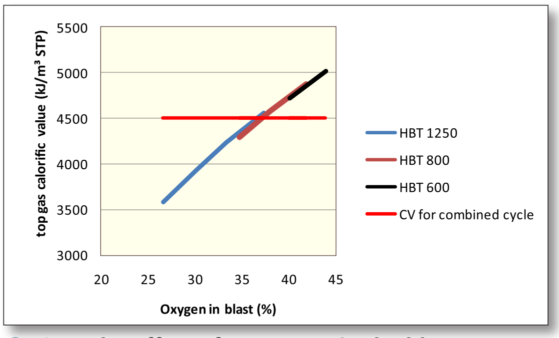

Fig 1 **The effect of oxygen % in the blast on top gas calorific value at various hot blast temperatures (typical)**

- BF top gas for combined-cycle power generation
- Flux injection
- Injection of pre-reduced iron ore fines

UTILISING BF TOP GAS FOR COMBINED-CYCLE POWER GENERATION

The classical Rankine cycle has an efficiency of 25-30% in power production from BF top gas, whereas combined-cycle power generation increases the efficiency by 10-15% to well above 40%. The efficiency of combined-cycle power generation depends on the calorific value of the top gas as well as the top gas hydrogen content. Combined-cycle is efficient if the calorific value of the top gas exceeds about 4,200-4,500MJ/m^3 STP. *Table 1* shows the calorific value of the blast furnace top gas at various levels of oxygen enrichment in the blast.

Top gas calorific value has increased in recent years as higher coal injection rates require higher oxygen enrichment of the blast (see *Figure 1*). Typically, an injection rate of 200kg pulverised coal per tonne hot metal (kg PCI/tHM) requires a minimum of about 26% oxygen in the blast. This is 5% above the natural level of 20.9%. An additional 1% enrichment is required for every 25kg PCI/tHM. Top gas ▷

Technical aspect	Units	Option A Base case	Option B	Option C
Coke rate	kg/tHM	292	262	262
Coal rate	kg/tHM	200	238	265
Pellets	kg/tHM	1,600	1,600	1,600
Hot blast temperature	°C	1,250	1,250	975
O_2 in blast	%	26.7	32.1	37.2
O_2 volume	Nm^3/tHM	66	110	153
CV of blast	kJ/Nm^3	3,647	4,115	4,521
Production	%	100	109	110
	Unit cost, US$	**Operating cost US$/ tHM**		
Pellets	85/tHM	136	136	136
Coke	210/tHM	61	55	55
Coal	85/tHM	17	20	23
Oxygen	60/1,000 Nm^3	4	7	9
BF gas/(28% yield)	-80/MWh	-22	-24	-30
Combined-cycle (yield 43%)				-16
Other costs		25	25	25
Total operating costs		**221**	**218**	**201**

Table 1 Hot metal cost based on mass balances of the blast furnace process

calorific value can be increased further by using oxygen enrichment rates well above the minimum required for PCI. Additional oxygen enrichment has the added advantage of a higher maximum productivity. It is even possible to lower the hot blast temperature, while simultaneously increasing oxygen enrichment and coal injection in order to compensate for the loss of sensible heat of the blast.

We have analysed the effect of high oxygen injection and high PCI with the help of our blast furnace mass and heat balance models and a simple economic model. The cost-price approach is very straightforward in that it takes an estimated US$25/tHM for all fixed costs excluding capital cost. Benefits of power generation are included in hot metal costs. Prices were taken from our own estimates of 2007 average prices in Western Europe.

The results are presented in *Table 1* which shows the technical conditions as well as cost-price effects. It can be seen that decreasing the coke rate from 292 to 262kg/tHM (option B) decreases the hot metal cost by about US$3/tHM. If the combined-cycle is applied together with a decrease in hot blast temperature (option C), cost decreases by another US$17. In any feasibility study local conditions and prices have to be taken into account. Note that in 'best of class' ironmaking operations, a sustained coke rate of 262kg/tHM was achieved for a longer period [1].

In addition, the pressure differential over the burden decreases when using a higher oxygen % in the blast, therefore there is a potential added benefit of a productivity increase of up to 10% – 'production' in *Table 1*.

The top gas calorific value can also be increased by enriching the top gas with natural gas, coke oven gas or BOF gas. Our analysis shows that it is worth enriching the blast furnace top gas to gain the efficiency benefits from the combined-cycle power generation. Nevertheless, the cheapest way to get higher calorific value top gas is by using more oxygen and coal in the blast furnace (results not shown). Critical for implementation of the technology is the control of raceway conditions as well as of the blast furnace inner gas flow by means of burden distribution.

FLUX INJECTION

Several authors have pointed out the potential benefits of the injection of fluxes into the furnace instead of via the ore burden [2-5]. Burnt lime, burnt dolomite, BOF or EAF slag can be injected together with the coal. One [3] used a system in which dolomite was ground together with coal for PCI. The effects of injection of fluxes are as follows:

Slag fluidity in the cohesive zone of the furnace

Because the primary melt formed in the cohesive zone has a lower basicity, it is expected that it will have better fluidity. This is illustrated in *Figure 2A*, where a slag phase diagram is given for the CaO – SiO_2 – FeO system showing the effect of lower basicity of slag liquidus temperatures moving from the lower yellow line to the upper white line corresponds with a decrease in basicity of 1.7 to 1.3.

In a blast furnace without flux injection the sinter gangue melts because of the presence of FeO which typically reaches a level of 70% during the formation of the primary melt. In normal operations at a sinter basicity (CaO/SiO_2) of 1.7, the primary melt moves along the yellow line when the FeO content of the melt is gradually reduced.

If the basicity is reduced to 1.3, the primary melt moves along the white line. In this example, the liquidus temperature decreases by some 500°C. In order to decrease the basicity by 0.2, about 8kg/tHM of burnt lime has to be injected. The slag liquidus diagram shown is simplified for illustration purposes only, as in reality the primary melt formed in the cohesive zone of the blast furnace contains many other components.

The benefits of a lower slag basicity in the cohesive zone are well known to blast furnace operators and, for example, are applied if the furnace is scheduled to stop. Typically, the slag basicity is lowered by about 10% for normal stops and by 20% for very long stops.

Slag fluidity in the raceway area In the raceway about 330kg of coke and coal is burned for every tonne of hot metal produced (the remaining coke is used for the direct reduction reaction and carbonisation of the hot metal). As the coke and coal are burned 25-30kg slag is formed from the coal and coke ash with a composition of about 50% SiO_2 and 30% Al_2O_3. This type of slag has very poor fluidity and drainage properties which can be improved by adding fluxes. In *Figure 2B* the slag liquidus ternary diagram of the $CaO - SiO_2 - Al_2O_3$ system is presented. Adding about 8kg of CaO to the 30kg $SiO_2 - Al_2O_3$ slag lowers the liquidus temperature from more than 1,700°C to about 1,500°C. The method is well known in coal gasification processes for producing slag with good fluidity. Reference [7] indicates a decrease of about 200°C in liquidus temperature of the slag on adding 25-30% of lime to an acid slag.

Hot metal silicon and sulphur Lower hot metal silicon and sulphur have been reported as a consequence of injecting dolomite [3]. The lower silicon comes from a lower silicon activity at the raceway border, since the authors kept the flame temperature constant. The lower sulphur is possibly due to the formation of more basic slag at the place where the sulphur is released from coke and coal.

Coal and coke rate We have estimated the effect of injection of burnt lime on the fuel rate and expect only about 1kg PCI/tHM additional coal injection to be required with an injection rate of 8kg/tHM burnt lime. In the case of dolomite injection an increase of 6.2kg coke at injection rate of 15kg/tHM dolomite was reported [3].

Permeability Injection of dolomite has led to an improvement in blast furnace permeability of about 5%, equivalent to an increase in production of 2-3%. Our revived interest in the subject comes from the observation that many companies experience limitations in reaching high coal injection levels. Improvement of fluidity of the primary melt in the cohesive zone may well prove critical for improvement in blast furnace permeability and thus for further increasing PCI.

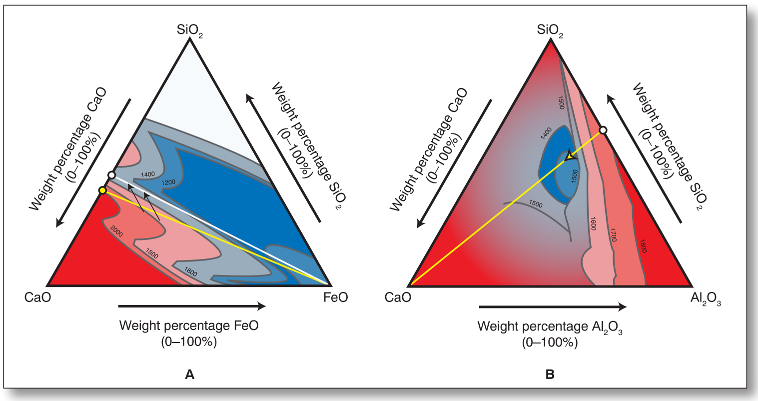

Fig 2 **Slag phase diagrams [6]. A: Cohesive zone: $CaO-SiO_2-FeO$ system, showing the effect of the reduction of iron oxides on slag liquidus temperature at basicity 1.7 (yellow line) and basicity 1.3 (white line) B: Raceway area: $CaO-SiO_2-Al_2O_3$ system showing the effects of addition of lime on slag liquidus temperature of melting coal and coke ash**

The major operational expenditure involved is the cost of the fluxes (burnt lime, burnt dolomite, BOF slag fines). Burnt lime injection would cost about US$1/tHM for an injection of 8kg/tHM, of which about half is compensated by the lower limestone requirements at the sinter plant. The remaining costs have to be recovered by increase of PCI (about 5kg/tHM) and/or additional production (0.5%).

We expect that fluxes can be injected via the coal injection system with very limited capital expenditure. It is tempting to suggest that the method is especially promising for plants operating on high slag rates and high Al_2O_3% in the slag, eg, in India.

USE OF PRE-REDUCED IRON UNITS

Various processes are available to reduce iron ore fines to ferrous materials with a low degree of oxidation. It is well known that the addition of pre-reduced iron units charged through the furnace top increases the furnace productivity. We have calculated the effects of the injection of pre-reduced iron ore fines through the tuyeres. To this end the mass and heat balances were calculated and the results compared to other studies of iron ore injection. Operational issues like wear of pipes/injectors were not considered.

The results are presented in *Table 2*, where we compared injection of pre-reduced iron fines or use of the same amount of hot briquetted iron (HBI) via the top, to an extent of 10% of the ore burden. The mass and heat balances show that the benefits of ore injection give about 20% of the cost benefits when compared with use of HBI charged via the top. The benefits have been estimated while not taking any additional charges for the HBI or reduced iron units into account. If the additional costs of HBI are taken into account, it is not economic to charge HBI into the blast furnace. ▷

	Units	Base case	HBI charging	Pre-reduced ore injection
Coke rate	kg/tHM	293	258	275
Coal injection	kg/tHM	200	200	200
O_2 content in blast	%	29.2	27.1	31.9
Pre-reduced ore	kg/tHM		94.5	94.5
Top temperature	°C	110	110	110
Flame temperature	°C	2,218	2,108	2,153
Potential productivity increase	%	100	103	107
Operating expenditure (- is advantage compared to base case), US$/ tHM				
From coke rate			-7.4	3.6
From oxygen			-1.3	1.1
From briquetting			0.5	
From injecting				0.5
From top gas calorific value			0.8	0.2
Total			**-5.0**	**-1.1**

Table 2 BF heat and mass balances with HBI charging and reduced ore injection

Concluding: pre-reduced iron ore injection gives only relatively small cost reduction compared to normal blast furnace operations. If reduced iron units are available, then it is probably more economic if the iron units are briquetted and subsequently used in steelmaking. In situations where cheap iron units, such as poor quality ore or plant reverts, are available (and in many areas, this material is abundant), injection of pre-reduced ore fines may be feasible. This feasibility will be highest for integrated plants without a sinter plant.

CONCLUSIONS

The blast furnace will remain an important production unit for hot metal for the coming 50 years, therefore it is worthwhile to analyse the potential for improvement efficiency and hot metal costs. In general, we expect that blast furnaces will be operated at higher oxygen % in the blast (well above 28-30%) and higher PCI rates (above 250kg/tHM).

There is a major cost saving possible if the blast furnace route is optimised from the point of view of oxygen enrichment of the blast, gas production and power generation. At higher oxygen % in the blast, the calorific value of the top gas becomes high enough such that the classical power generation based on the Rankine cycle can be replaced by the combined cycle. The efficiency of power generation will then increase from below 30% to well above 40%. The feasibility of the technology depends on local circumstances and requires a feasibility study.

Further increase in PCI rates is only possible if the permeability of the blast furnace is improved and further study of the injection of fluxes is required. Injection of pre-reduced iron ore fines into the blast furnace is an option for poor quality raw materials on site. If a fines reduction process is available, it can even be an alternative for a sinter plant. **MS**

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