



FOCUS

The magic of ironmaking

Iron is an essential ingredient in the manufacture of steel, which, in turn is a critical component in the production of engineering goods. However, the making of quality iron has been a challenge down the ages. For India, what is crucial is the indigenisation of ironmaking processes based on local raw materials and conditions, together with use of appropriate technology. Prof. Gour Gopal Roy takes us on a magical journey through these processes in the making of superior iron and steel



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ET me start with an illustration that represents the major products of a steel plant and various routes to achieve those products from iron ore in a novel composition temperature diagram.¹

Figure 1 shows the positions of raw materials such as pure hematite with 30% oxygen and scrap almost pure iron with minor oxygen and carbon in it. Various products like direct reduced iron (DRI), hot metal (HM) and liquid crude steel (CS) are also shown in the temperature composition diagram. DRI is a solid state reduction product achieved at comparatively lower temperatures (800-1100°C) and with carbon content in the range

0-2%. Hot metal is usually tapped at around 1300-1400°C with carbon content around 4-5%. Steel is produced at 1600°C with carbon less than 1% and oxygen around 1000ppm.

Now, how do we approach these products, starting from pure hematite? We produce DRI or sponge iron by solid state reduction process like coal-based rotary kiln, or gas-based shaft furnace processes like midrex, HYL etc. Coal-based process requires higher temperatures (>1000°C) to sustain in-situ CO generation by carbon gasification that is highly endothermic. In contrast, gas-based direct reduction (DR) processes are carried out at comparatively lower temperatures (800-900°C), using reformed natural gas. In case of blast fur-

nace, we can see that majority of oxygen is removed by 1000°C at solid state in the upper dry zone of the furnace. In the lower part of the furnace only melting and carburisation takes place.

Hot metal of similar quality to that of blast furnace can also be produced by smelting reduction (SR) process using non-coking coal. Here, the reactor is different. Blast furnace (BF) is a complex reactor maintaining dry zone and wet zone interfaced by a cohesive zone in a single reactor. Although BF is a very efficient reactor, it imposes very stringent raw material requirement to maintain such complex internal structure suitable for efficient counter current gas-liquid-solid heat and mass exchange. For example, BF prefers agglomerated bur-

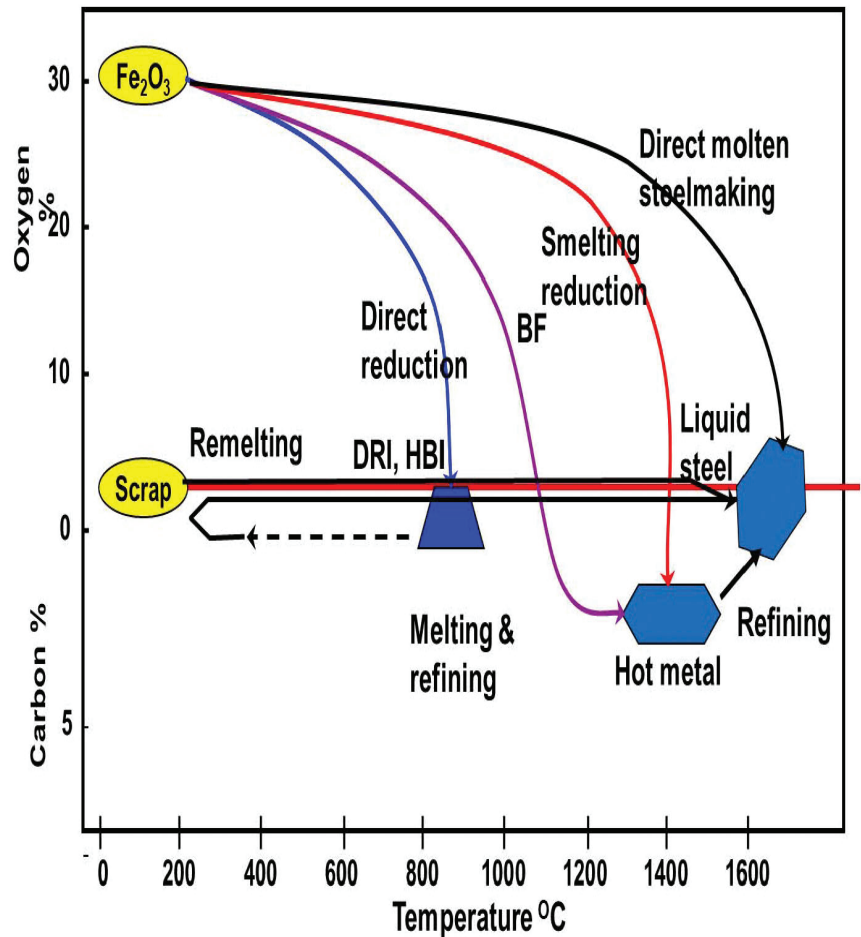
den like sinter and pellets with better strength over lumpy run of mines ore to minimise fines generation during their decent in BF and maintain proper bed permeability for counter current gas-solid reaction. In spite of PCI injection, BF requires a minimum amount of coke (~280kg/thm) to hold the overburden because in the lower part of the furnace everything except coke is liquid. In order to compromise with the quality of raw material like lumpy ore and 100% non-coking coal, smelting reduction introduces two separate reactors – one for pre-reduction of the burden and other for melting and rest of the reduction in liquid state. Since these two reactors are decoupled and independent and connected by solid and gas stream externally, the quality of raw material is not important.

This is a two-stage SR process, inspired by energy-efficient BF process. However, single-stage process is also available but with higher coal rate. In general, carbon rate of SR process is much higher than BF process. Therefore, off-gas credit of SR process is higher and unless the off-gas is utilised for DRI production/power generation, the process does not become economical. So, in the diagram, we can see majority of oxygen in SR process is removed under liquid state at high temperature. Now, hot metal can be refined using oxygen to remove the carbon and get the liquid steel. Or the DRI, scrap can be melted in EAF and refined along with HM to yield liquid steel.

Finally, can we have a direct steelmaking process at 1600°C to produce liquid steel from iron ore? Not yet; but it remains a potential route of steelmaking.

The scenario of input material landscape for steelmaking is changing rapidly. Initially, in an integrated steel plant hot metal was the major input material for steelmaking and it was supplemented by plant generated scrap. Today, with the advent of technology like continuous casting, internal scrap generation

Figure1: Various approaches from iron ore to liquid iron



has decreased but end-of-life scrap is increasing with increasing usage of steel. Besides, DRI, or sponge iron production using non-coking coal and synthetic gas is on the rise. Since, sponge can be produced independently using cheaper raw material, various integrated steel plants are keeping captive DRI units or outsourcing from market at cheaper price. So, the cold charge (scrap, DRI) is increasing progressively in the proportion of input material for steelmaking.

Since BF has limitations in melting cold charge, EAF emerges as a better alternative to refine raw materials containing different proportion of cold and hot

charges. Besides, use of scrap in EAF is also considered carbon neutral as scrap is already pure iron and does not require any reduction. However, electricity that is used in EAF should be from renewable source to make it truly carbon neutral and may be termed as green technology. Therefore, share of EAF in producing steel has increased over the years, especially during the period 2012-20, and today around 30% of 1.8 billion metric tons of steel produced in the world is routed through EAF.² Scrap also forms the lion's share as metallics in world EAF steel production; around 575 metric tons of scrap is recycled per annum.

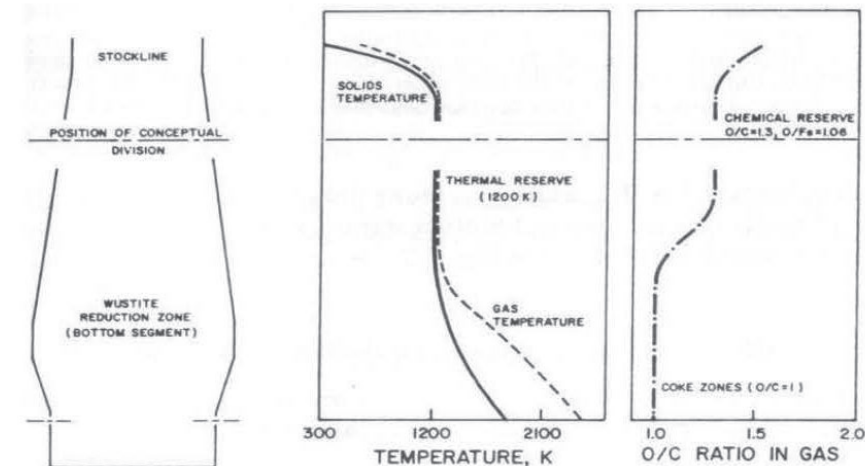
BLAST FURNACE, ITS DEVELOPMENT

AMONGST all ironmaking technologies, the blast furnace still holds its dominant position today. It has remained up-to-date and competitive with new technologies. Some of the benchmarks of blast furnace today are hot metal production 8000-10,000 tpd, fuel rates around 500 kg/thm (280 coke+220 kg PCI), and furnace availability 95-98%. Major developments in blast furnace have taken place by 2000³ (Figure2).

It started with iron ore beneficiation and use of overseas rich ore; idea was to reduce the gangue and the wet zone in blast furnace where the major pressure drop takes place. It followed with the use of iron ore pellets, agglomerated iron ore burden with higher strength and regular spherical shape, which provides better bed permeability in the dry zone enhancing indirect reduction and consequently yielding lower coke rate and higher productivity.

Subsequently, the auxiliary injection through tuyere in the form of oil injection was introduced, which partially supplemented the function of coke like heating and reduction, reducing coke rate. Since oil is hydrocarbon, it also produced H₂ along with CO, and it improved the indirect reduction. As a result, oil injection replaced coke more efficiently with a replacement ratio (kg of coke saved per kg of oil used) greater than 1. It is to be mentioned that indirect reduction takes place in the upper part of the furnace utilising the CO generated in the lower part of the furnace. Direct reduction, where carbon directly participates in the reaction through in-situ CO generation by carbon gasification reaction [Eq.(1)], takes place only in the lower part of the furnace where endothermic gasification reaction can be sustained. Direct reduction is not a problem in blast furnace due to large availability of carbon; while in-

Figure2: Development in blast furnace ironmaking



direct reduction in the upper part of the furnace is limited by the uniform distribution of CO gas in large cross-section of BF for iron ore reduction. Therefore, indirect reduction can be ensured by good permeability of the bed, which in turn can be ensured by good quality burden. Indirect reduction can also be ensured by availability of hydrogen because it is a better reductant than CO, both thermodynamically and kinetically.

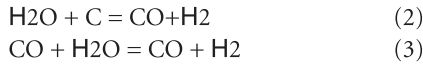


Next development in blast furnace was the introduction of preheated air blast. With the advent of blast furnace stoves, air blast could be preheated to 1200°C. Supply of large amount of sensible heat through preheated air blast, supplements the heating by carbon oxidation and reduces the coke rate.

Subsequently, it was noticed that large amount of heat also emits through off-gas as sensible heat of nitrogen as air contains 79% nitrogen by volume. It is to be noted that nitrogen also plays a crucial role in heat exchange through the long shaft

in the blast furnace. It increases the heat capacity of the gas and supply the sensible heat to meet up the heat demand of the entire solid bed in the long shaft for preheating. But, heat capacity of BF gas in the upper part of the furnace should not exceed much beyond the heat required by the solid, such that gas leaves the furnace at around 100-150°C. Thereafter realisation came to decrease the amount of nitrogen in air through oxygen enrichment to reduce the volume of air blast, blast furnace gas, and its heat capacity. Oxygen enrichment also increases the flame temperature. Therefore, it is usually accompanied with most of the auxiliary injection that increases heat capacity of gas and reduces flame temperature, like fuel and steam injection. Steam injection introduces H₂ in the BF gas through endothermic carbon gasification [Eq.(2)] by steam in the lower part of the furnace and mildly exothermic water gas shift reaction [Eq.(3)] in the upper part of the furnace. Since steam injection introduces H₂ as reductant, it is good for indirect reduction and lowering coke rate; but as it causes endothermic reaction in the lower

part of the furnace, it is usually accompanied by oxygen enrichment.



The oil crisis in the 1970s forced the steel producers to shift to pulverised coal injection (PCI) as an alternative to oil injection in blast furnace. Gradually the technology for PCI injection matured and today PCI rate of 200-220/thm is a benchmark.

Campaign life of blast furnace has increased manifold with availability of blast furnace being 95-98% as benchmark today. This has happened with improved refractory and mainly with improved cooling arrangement of refractory using copper staves. These are water cooled rectangular copper plates that cool the refractory from being overheated and develop weakness.

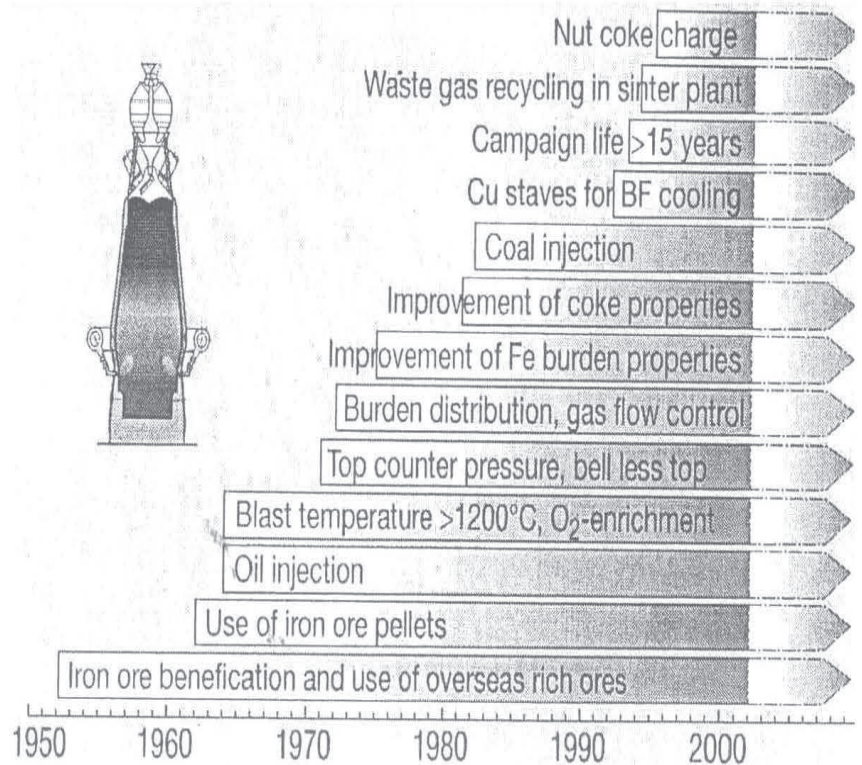
Comparatively recent research has introduced the concept of nut coke (a product of coke oven), which is usually smaller in size (20-40mm) than normal coke (80-90mm). Nut coke has been found to improve the bed permeability significantly in the dry zone as well as cohesive of the blast furnace when it is optimally used.⁴ Nut coke with some additives, has also been found to be very reactive. However, excessive replacement of regular coke by PCI and nut coke reduces the coke layer thickness, which increases the gas flow resistance and pressure drop significantly. Nut coke also increases the resistance to liquid percolation through deadman coke; therefore, their use should not exceed an optimum amount (10-20% of total coke input) in the furnace.

Potential technologies for blast furnace

Low temperature low emission technology

Blast furnace is a counter current gas solid reactor that in fact helps in gas utilisation in the furnace. Let us take a brief

Figure3: Conceptual division of blast furnace as two-stage reactor

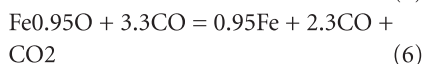
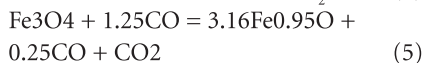
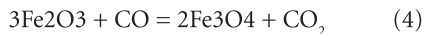


look at iron oxide reduction. Reduction of hematite takes place in three sequential stages: hematite (Fe₂O₃) to magnetite (Fe₃O₄); magnetite to wustite (wustite represents non-stoichiometric lowest order iron oxide, Fe_xO where x is typically 0.95); and wustite to iron. Thermodynamically, it is found that indirect reduction of hematite to magnetite by CO is almost irreversible with almost zero equilibrium requirement of CO; in other words CO utilisation is 100%, while the CO utilisation is non-zero for subsequent conversion of iron oxides and also it depends on temperature. For example, for magnetite to wustite conversion, CO utilisation at 900°C is 80% and for wustite to iron conversion it is only 30%! It means that for conversion of one mole wustite to iron, CO requirement is 3.3 moles at 900°C; in other words out of 3.3 moles of CO only one mole of CO will be used for

conversion of wustite to iron, while rest 70% CO, i.e. 2.3 moles of CO will remain in equilibrium with other constituents. It is to be mentioned here that 900°C is an important temperature in blast furnace because a large middle portion of the furnace remains at this temperature, called the isothermal zone, which allows the heat exchange between gas and blast furnace burden to complete separately, both at the lower and the upper part of the furnace. All indirect reduction of wustite takes place in isothermal zone and wustite-iron equilibrium is also attained in the upper part of the isothermal zone, called the chemical reserve zone. This allows the blast furnace to be treated as two-stage reactor⁵ (see Figure3), where heat and materials balance could be made independently in the lower part of the furnace to develop a complete predictive model to define minimum coke rate,

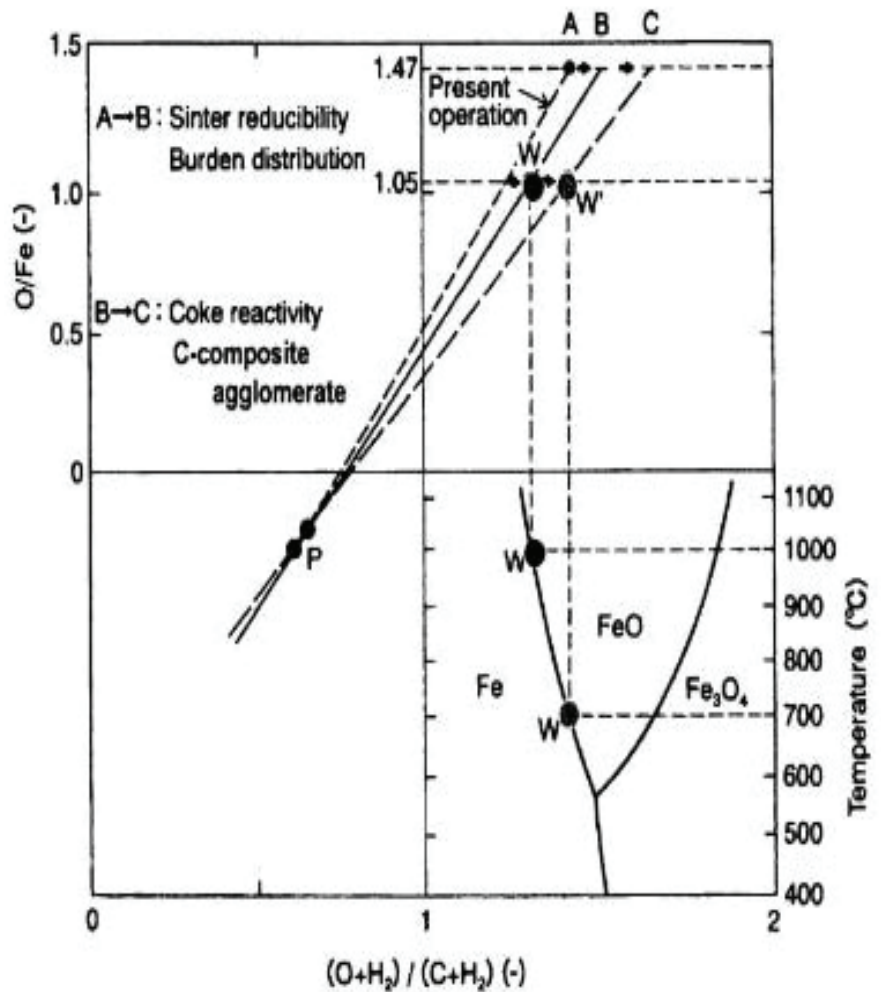
called the RIST diagram or, operating line in blast furnace.⁵ Temperature of isothermal zone is an important concern for fuel efficiency which has been discussed in a subsequent section.

Since blast furnace is a counter current gas solid reaction, hematite and magnetite reduce in the locations up in the blast furnace as CO requirements are low and their oxygen dissociation pressures are also high. Wustite having higher requirement of CO are reduced lower part in the furnace and it undergoes both direct and indirect reduction at high temperature. Considering the utilisation factors for various iron oxides at 900°C, indirect reduction of iron oxides may be given by Eqs.(4)-(6) and direct reduction of wustite by Eq.(7).



So, it is obvious that direct reduction is economic in carbon while indirect reductions are expensive. The fuel economy may further be enhanced if ore oxygen is optimally partitioned between direct and indirect reduction such that CO evolved from direct reduction is just sufficient to support rest of indirect reduction. Stoichiometrically, it can be shown that 429 kg of ore oxygen is required to be removed to produce one ton of iron, out of which 302 kg of oxygen is associated with wustite only. Therefore, CO utilisation in blast furnace can be maximised if the wustite oxygen is optimally partitioned between direct and indirect reduction. It can be shown readily that when 231 kg of wustite oxygen (54% of total removable ore oxygen) is removed by direct reduction, it is just sufficient to sustain the rest of wustite oxygen removal by indirect reduction.⁶ It can further be shown that the 70% unutilised CO after indirect reduc-

Figure4: Fe-C-O phase diagram superimposed with RIST diagram



tion of wustite in this case is also sufficient to take out the rest of the ore oxygen from higher oxides during the counter current gas solid interaction in blast furnace. Finally it yields a CO utilisation of 86% in blast furnace and it is the maximum utilisation of CO; in other-words in CO, CO₂ mixture in the off-gas, %CO cannot be lowered below 16%.

It is to be noted here that CO utilisation for indirect reduction of wustite further decreases with increase in temperature and vice versa (see Figure4). Therefore, if the wustite reduction could be carried out at comparatively lower

temperatures, the overall CO utilisation efficiency could further be improved, reducing the coke rate and emission. The minimum coke rate in blast furnace for a given burden material with fixed heat demand, can be calculated by heat and material balance in lower part of the furnace independently, which yields a fixed straight line, the slope of which provides the coke rate (known as RIST diagram). The line (called the optimum operating line) is pinned by two points; one arising out of heat balance called the thermal pinch point (H) and the other by the equilibrium point for wustite reduction

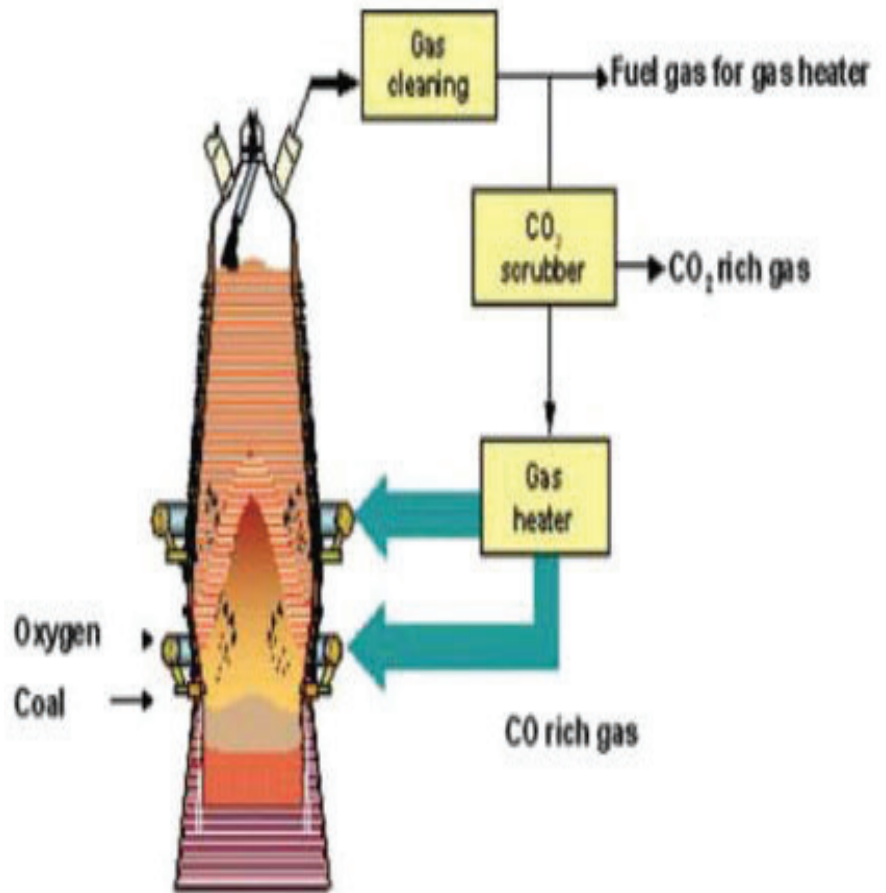
(W). The +ve y axis gives the O/Fe ratio in iron oxide, -ve y axis provides the blast oxygen and x-axis provide gas composition in terms of atomic ratio of oxygen to carbon (O/C) in BF gas. Figure4 shows a diagram, where the Fe-C-O phase diagram is superimposed on the operating line in RIST diagram. In this figure x-axis is represented by $(O + H_2)/(C + H_2)$, to include the effect of H₂ in gas composition. Since the hydrogen utilisation efficiency at higher temperature is greater than CO, the Fe-C-O phase diagram is shown here, as it controls the reduction efficiency.⁷

Now it can be seen that as the temperature of reduction decreases, the wustite equilibrium point on operating line shifts to the right (W to W'), which allows the minimum coke rate in the furnace to reduce further (shift from B to C). This is referred as low temperature and low emission technology for blast furnace. However, lowering the wustite reduction temperature is not easy because to sustain the wustite indirect reduction at lower temperature, CO supply by direct reduction of wustite has also to be ensured at lower temperature. This is challenging as direct reduction is highly endothermic that requires higher temperatures. It has been shown by researchers that temperature of direct reduction, or carbon gasification reaction that controls the direct reduction, can be lowered by: i) increasing the reactivity of coke; ii) presence of impurity in coke that catalyses carbon gasification reaction; and iii) use of iron ore-coal composite pellets that brings in intimacy of carbon and iron ore particles.⁷ It is to be mentioned that sinter reactivity is also required to be high for indirect reduction to achieve its equilibrium (shift from A to B, in Figure4).

Top gas recycling blast furnace (TGR-BF)

Today CO₂ emission is an important parameter to judge the sustainability of ironmaking process. In spite of all above advancement for more efficient and productive blast furnace, CO₂ emission is

Figure5: Schematics of top gas recycling blast furnace



still at an average of 2 ton of CO₂ per ton of hot metal produced. There are some potential techniques that can reduce the CO₂ emission significantly. For example, ULCOS's top gas recycling blast furnace (TGR-BF). ULCOS stands for ultra-low CO₂ steelmaking, a European consortium of 48 companies and organisations working for mitigation of CO₂ emission for steelmaking. Steelmaking is mainly routed through BF-BOF, where BF contributes to maximum CO emission. The schematics of BF-TGR is shown in **Figure5**.⁸

In this version of BF, oxygen at room temperature is charged in place of pre-heated air blast and top gas is recycled back

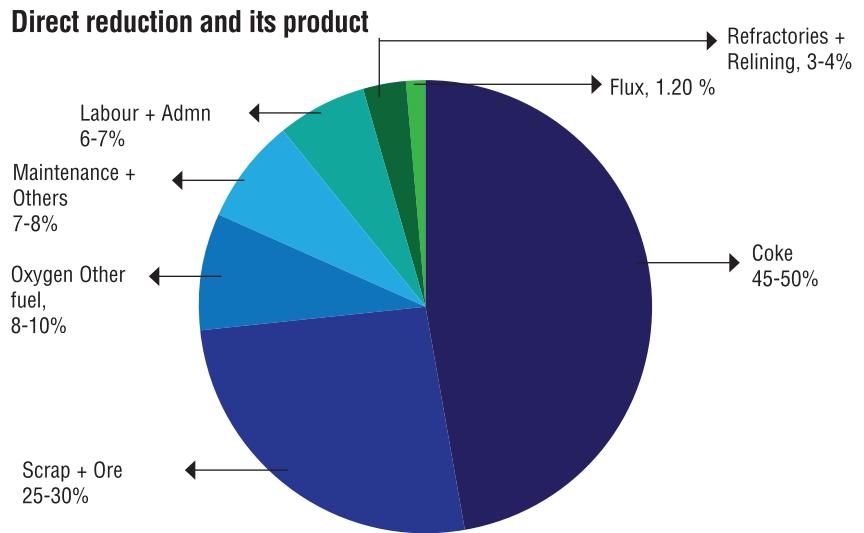
after scrubbing CO₂. Recycling of top gas, reduces carbon consumption by 20% and CO₂ emission by 50%. On counts of demerit: Since heat capacity of gas decreases significantly (in absence of nitrogen), to maintain upper part heat balance, heat capacity of the solid has to be decreased either by improving burden quality or decreasing the shaft height. Realising this problem, another version of TGR-BF has emerged using oxygen enriched air blast.⁹ Besides, recent studies also showed that downstream gas from BF decreases significantly with TGR-BF, which causes fuel shortage in the plant and re-generation of such fuel externally again adds to CO₂ emission.

DRIVING FORCES FOR ALTERNATIVE ROUTES OF IRONMAKING

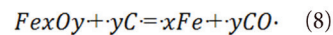
THE reductant carbon in blast furnace is used in the form of coke, a strong, consolidated product of coal produced by heating coking coal (a special variety of coal used for coke making) in absence of air in coke oven. The coking coal reserve in India is very limited, that too with high ash content. Therefore, India mostly depends on the imported coking coal, primarily from Australia. Accordingly, the cost of coke constitutes around 45-50% of the total cost of hot metal production in blast furnace (Figure 6).¹⁰ This value may be little lower today as significant amounts of coke is replaced by cheap PCI to the tune of 200kg/thm; but coke still constitutes dominating fraction of total cost for producing hot metal. On the contrary, India has a large reserve for non-coking coal, which has very limited use in steel-making, except its use as pulverised coal injection (PCI) in BF. India has also large waste dumps in the form of off-grade iron ore fines, iron bearing waste dust, sludge from plants, which otherwise pollutes the atmosphere. So, it is aimed to utilise iron bearing solid waste, and non-coking coal through alternative routes of ironmaking. Coke ovens and sinter plant (ore agglomeration plant) also pollutes atmosphere. Therefore, alternative routes are evolving for directly utilising off-grade iron ore fines, iron bearing solid waste, non-coking coal, synthetic gas and producing value added sponge iron (direct reduction processes), which can subsequently be melted in electric furnace; or directly producing liquid iron using non-coking coal (smelting reduction processes).

Direct reduction (DR) processes may be broadly classified into two categories: i) coal-based DR process; and ii) gas-

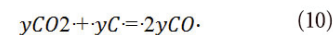
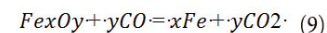
Figure 6: Cost breakup of hot metal



based DR process. In case of coal-based DR process, iron oxide is heated in the presence of carbon at temperature 1000-1100°C, to reduce iron oxide through in-situ generation of CO by carbon gasification, which is called the direct reduction. The overall reaction may be written as:

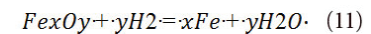


Actually the reaction takes place by gaseous intermediates like CO and CO₂, through the following two reactions:

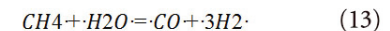
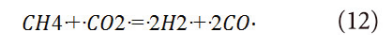


In case of gas-based process, reformed natural gas is used to reduce iron oxide in solid state to produce sponge iron. Re-

forming of natural gas produces both CO and H₂. So in addition to reaction (2), the second reduction reaction for gas-based reduction may be given as:



The reforming of natural gas can be done either by CO₂ or H₂O as follows:



The product of direct reduction process is called the direct reduced iron (DRI) or sponge iron. Sponge iron neither looks like sponge under the naked eye, nor is it sponge-like soft. But if seen under the microscope, one can see a spongy texture, with lots of gas holes in it (Figure 7).¹¹ Sponge iron can be directly charged in electric furnace as hot charge, or may be hot briquetted for subsequent

use as cold charge. Sponge iron, especially gas-based sponge, is prone to re-oxidation and there are methods for passivating it. Coal-based sponge is inherently protected against re-oxidation through a slaggy layer. Gas-based DRI is given a protective layer of cementite through cracking of natural gas during its cooling. Hot briquetting also reduces the specific surface area of the sponge, which restricts its re-oxidation.

Evolution of direct reduction processes

The evolution of DR processes started as early as in 1930 and processes are evolving still today. A brief evolution is given in **Table1**.¹²

During 1930-50, all coal-based processes were developed. In Högånäs process, saggars (cylindrical crucible) filled with alternate layers of iron ore and coal fines are reduced in tunnel kiln. Here saggars are put on rail wagons, which are pushed through the gas-fired long tunnels, called the tunnel kiln. The iron oxide inside saggars get self reduced in the presence of carbon through heat supply from furnace atmosphere across the saggars. Heat transfer across the saggars limits the process efficiency. Among other limitations, it also requires large land space for layout. So, processes based on shaft furnace (counter current gas solid cylindrical reactor) evolved subsequently. In Wiberg process, a coal bed is reformed by steam and the synthetic gas (CO/H₂) is passed through the shaft furnace.

From the 60s onwards the much cleaner gas-based DR process evolved, especially for countries with large availability of natural gases. HYL-I process, based on static reactors (four static reactors in series), was developed in Mexico, where natural gas is abundant. FIOR (fluidised iron ore reduction) invented in the US, uses a train of fluidised beds to convert iron ore fines to hot briquetted iron. Unlike shaft furnace, fluidised bed reactors operate at high pressure for favourable

Figure7: Appearance of sponge iron under microscope

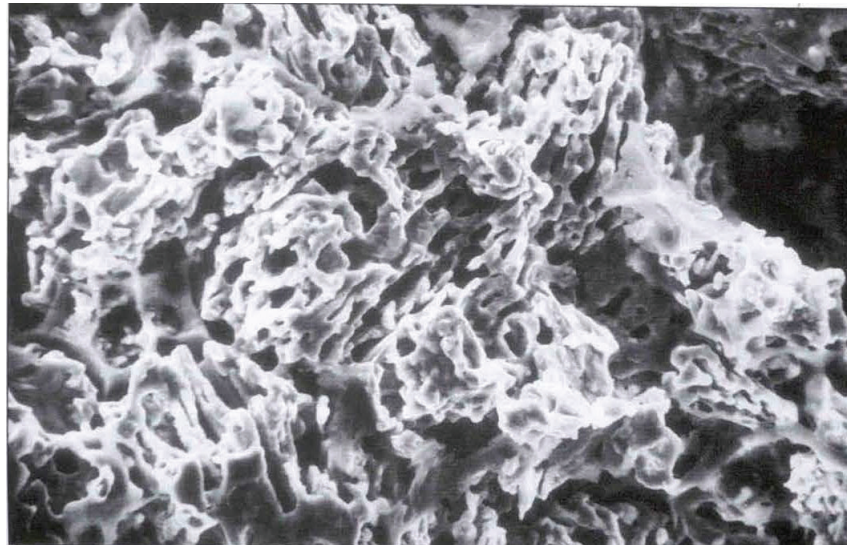


Table1: Evolution of DR processes

Time	Main methods developed	Main processes	Remarks
1930-50	Saggars in tunnel kilns Small shaft furnaces Rotary kilns	Hoganas Wiberg Krupp, Iurgi	Based on coal
From end-50s	Static reactors Fluid bed reactors	HYL I FIOR	Based on gas
From end-60s	Shaft furnaces (up to 14 processes)	MIDREX, HYL III	Based on gas
Current	Rotary hearth furnaces Improved fluid bed processes Self reforming processes	Fastmet, Inmetco FINMET HYL IV	Based on coal Based on gas

fluid dynamics for gas-solid interaction and reduction. The major problem of this process lies with continuous operation at high pressure. Therefore, FIOR and subsequently FINMET could not see much success and shaft furnace-based processes got importance. The limitation of HYL-I process with four static reactors was rectified in terms of single continuous shaft reactor and with steam reforming of natural gas as usual, gave rise to 3rd generation HYL-III in the 70s. Another popular gas-based shaft furnace process called MIDREX(R) Process (owned by Kobe Steel) also appeared in this period. The process utilises off-gas CO₂ from re-

duction shaft for reforming natural gas.

After the 90s, the RHF (rotary hearth furnace)-based process also emerged mainly to utilise the iron bearing solid waste from steel plant. As the name suggests, in RHF, the hearth rotates in a circular path and carries the charge material through different temperature regimes to produce the sponge. The doughnut-shaped circular reactor optimises the space. The charge material is usually naturally cured composite pellets/briquettes made of iron ore fines/iron bearing solid waste and some carbonaceous material like coal fines. Since the material remains stationary, low strength of such pellets/

briquettes may be accommodated. Fastmet, Inmetco are some of the processes based on RHF technology. The DRI from RHF may be melted in SAF (submerged arc furnace)/EIF (electric iron making furnace)/EAF (electric arc furnace), or, even in BF as metallised iron, depending on the grade of sponge that in turn depends on the total iron content of raw material. HYL-IV process is the most advanced HYL technology that carries out self-reforming of the natural gas in the shaft furnace itself using nascent iron as the catalyst. This eliminates the additional reforming unit and costly nickel catalyst for steam reforming of natural gas. **Table2** presents the various routes of DR processes with their inputs and subsequent processes to convert to liquid steel.¹²

While India has a major advantage over many other countries including China, in terms of rich iron ore reserves for the next 50 years, it is crippled with limited and poor quality coking coal. This prompted India to explore alternative routes of ironmaking using non-coking coal, natural gas. In India, largely available non-coking coal and offshore gas along with rich iron ore, have prompted several direct reduction routes to emerge successfully. This also helped to disperse Indian steel production from eastern India due to proximity of both coking coal and iron ore. The direct reduction (DR) process that entered India in 1981 has grown at a faster rate. Today there are more than 180 DRI units and India has surpassed DRI production of gas rich countries like Venezuela and Mexico, where DRI is produced exclusively by gas-based processes. India produces DRI using both coal and gas and today it is the largest producer of DRI in the world (30 Mtpa).²

Brief evaluation of DR processes

Rotary kiln process

The most popular reactor for coal-based DR is the rotary kiln (**Figure8**). In this

Table2: Various routes of DR processes

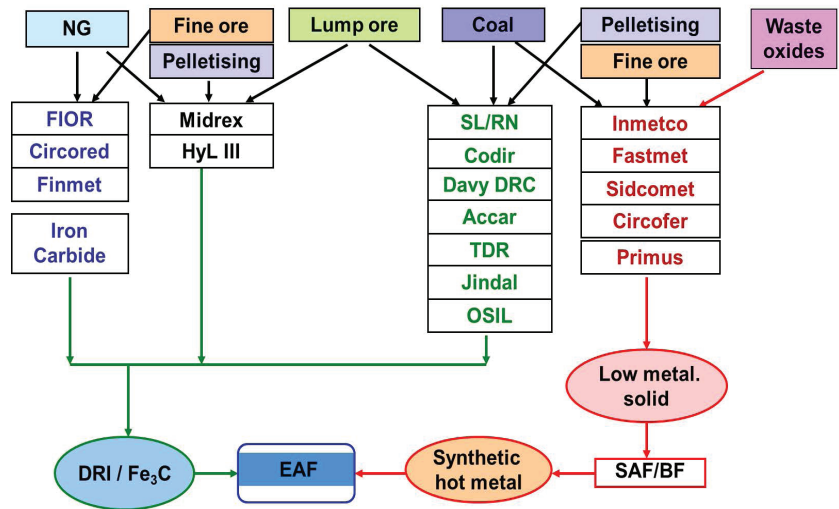
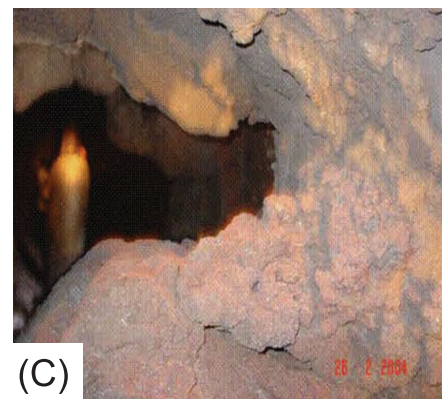
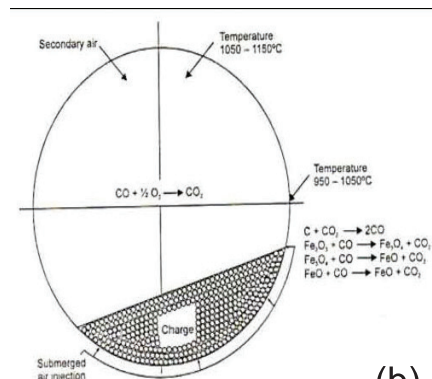
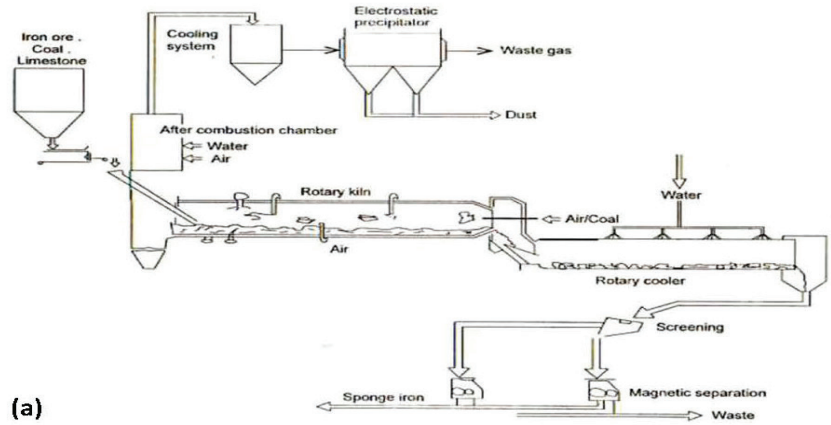


Figure8: (a) Schematics of rotary kiln process; (b) cross-sectional view of kiln; (c) accretion blocking path of material



reactor, iron ore, coal, limestone are charged at input and subsequently the material moves through a coal-fired rotating cylindrical reactor, called the rotary kiln. Here, coal acts both as heat generator as well as reductant. Kiln rotation renews the solid surface for reduction. The kiln is slightly inclined and, assisted by kiln rotation, it helps in pushing the solid from input to the discharge end. Solid loading in the reactor is only 15% to allow large volume of dust laden gas to pass through the reactor, which limits its productivity. The maximum capacity of a typical rotary kiln is 500 tpd (tons per day). So for producing more, several kilns need to be installed, which increases both capital expenditure as well as operating cost. Dust laden off-gas needs to be cleaned to separate the particulates and make the process environment friendly. Specific energy requirement is also quite high at 25 GJ/tDRI³ (may be unfavourably compared with 25-27GJ/tcs by BF-BOF route, which is a refined liquid product of iron). Of this input energy around 35% leaves through off-gas. Therefore, the process becomes uneconomical unless the cleaned off-gas is used for power generation. Another important issue with rotary kiln is the accretion formation, which takes place when the local temperature exceeds the ash fusion temperature. Therefore, furnace temperature should not exceed 1050°C. This can be achieved by controlling post-combustion of CO (by controlling secondary air), using high reactive coal that promotes endothermic carbon gasification, optimising kiln rpm that segregates fines on the wall.

The quality analysis of coal-based and gas-based DRI is given in **Table3**. The product of coal-based DRI is prone to capture sulphur from coal ash due to intimate contact. Lime is used to neutralise the sulphur content in coal-based DR. The rotary kiln process might be improved in terms of productivity and cleanliness by using coal-based synthetic gas produced in a separate reactor.

Table3: Typical quality analysis of coal and gas-based DRI [3]

Items	Coal-based	Gas-based
Fe (t)	90-91	93-94
Fe (M)	80-82	86-88
Carbon	0.1-0.3	1-2
Sulphur	0.040-0.050	0.008-0.010
Phosphorus	0.040-0.050	0.030-0.040

It is heartening to note that to suit Indian raw materials, several rotary kiln-based DR processes have developed indigenously. TISCO direct reduction (TDR) process, with some unique features like submerged air injection, maintaining flat temperature profile along the entire length of the kiln, was commercialised to set up its first 300tpd unit at Tata Sponge, Joda. The process was scaled up to 350tpd with 7.5MW power generation in association with Lurgi and added in 1998, and a 3rd kiln with capacity 500tpd and 10MW power generation was added in 2006. The sulphur content of TDR sponge is quite low 0.02 to 0.04%.³

Jindal Strip Ltd, Hissar developed the Jindal process for sponge iron, and installed its first commercial plant at Raigarh, MP in 1989 using in-house design, engineering and technology and production of the first 300tpd started in 1991. Today, it has six units with capacity 300tpd and four units with 500tpd (total 1.37 Mtpa). Coal washeries are set up to reduce ash content of coal from 40% to 25%, for subsequent use in the kiln. The waste gas, leftover coal char, coal fines, reject of coal from washeries are utilised to generate 100MW power, and this makes the plant produce sponge at the lowest price.

OSIL (Orissa Sponge Iron Ltd) started sponge iron production with ACCAR (Alis-Chalmers Controlled Atmospheric reduction) technology; but the process was indigenised significantly to cope with local conditions and raw material giving

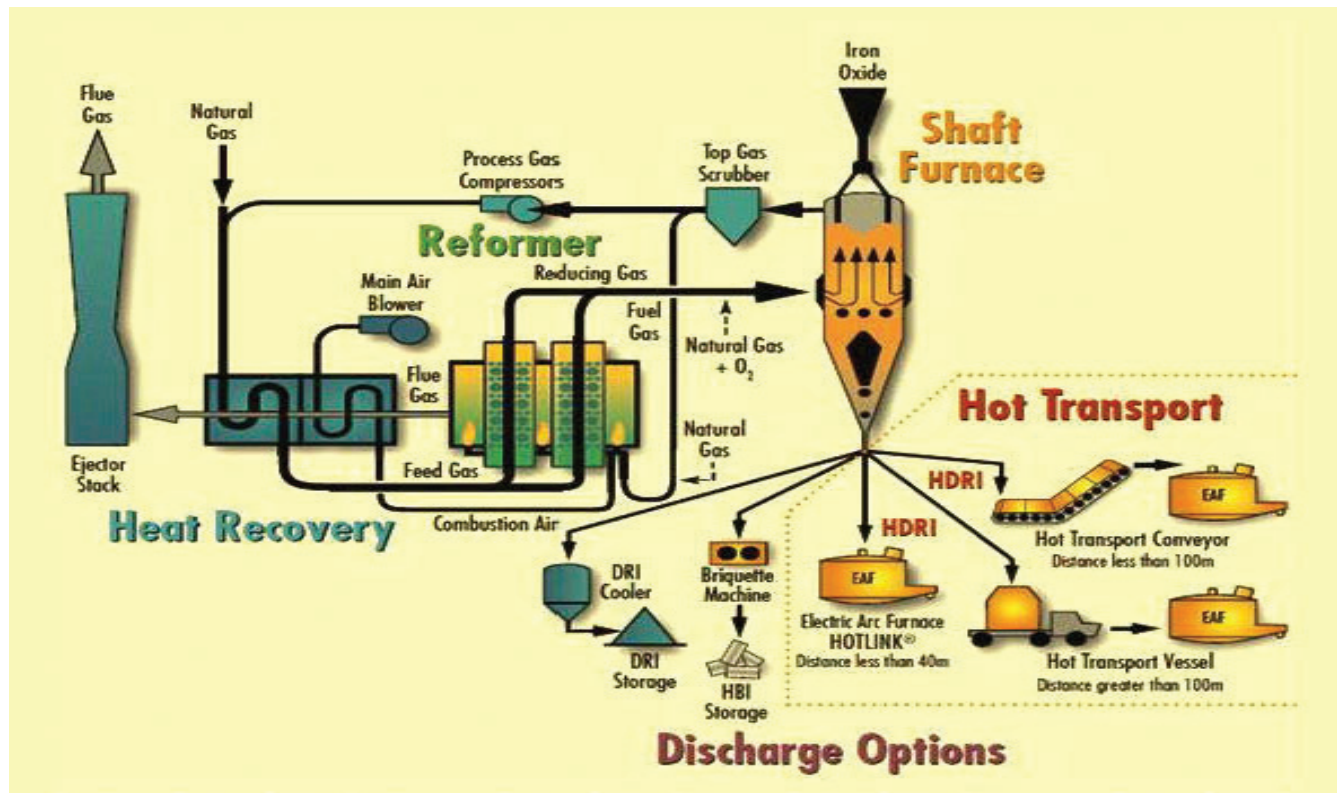
rise to new technology called the OSIL process. Some of the added features are replacement of oil by non-coking coal, raw material beneficiation, distribution in secondary air, etc.

Shaft furnace-based processes

Gas-based DR processes are primarily carried out in shaft furnace, which are cylindrical counter current gas solid reactors. The basic units of shaft furnace include a gas generation unit, and a shaft furnace reduction unit. Reducing gas (a mixture of CO and H₂) is primarily produced by reforming natural gas either by CO₂ or steam. Places where natural gas is not available in plenty or, cheaply, synthetic reducing gas (syn gas) can be generated by oxidising coal bed using steam and oxygen, which can subsequently be used in reduction unit. Advantage is that high ash inferior grade coals, which are not suitable even for rotary kiln process, can be directly processed to syn gas. It is also possible to use the waste gas from other processes like coke oven gas (COG) in the reduction shaft. Special technologies are available today to utilise syn gas and COG in reduction shaft.

Two commercialised shaft furnace-based DR processes are MIDREX-(R) and the HYL processes. HYL is owned by Mexico-based company Hojalata y Lámina SA and it uses steam reforming of natural gas. MIDREX(R), which is owned by Kobe steel, uses off-gas CO₂ from reduction shaft for reforming natural gas. MIDREX reduction unit oper-

Figure9: Flow diagram of MIDREX(R) process



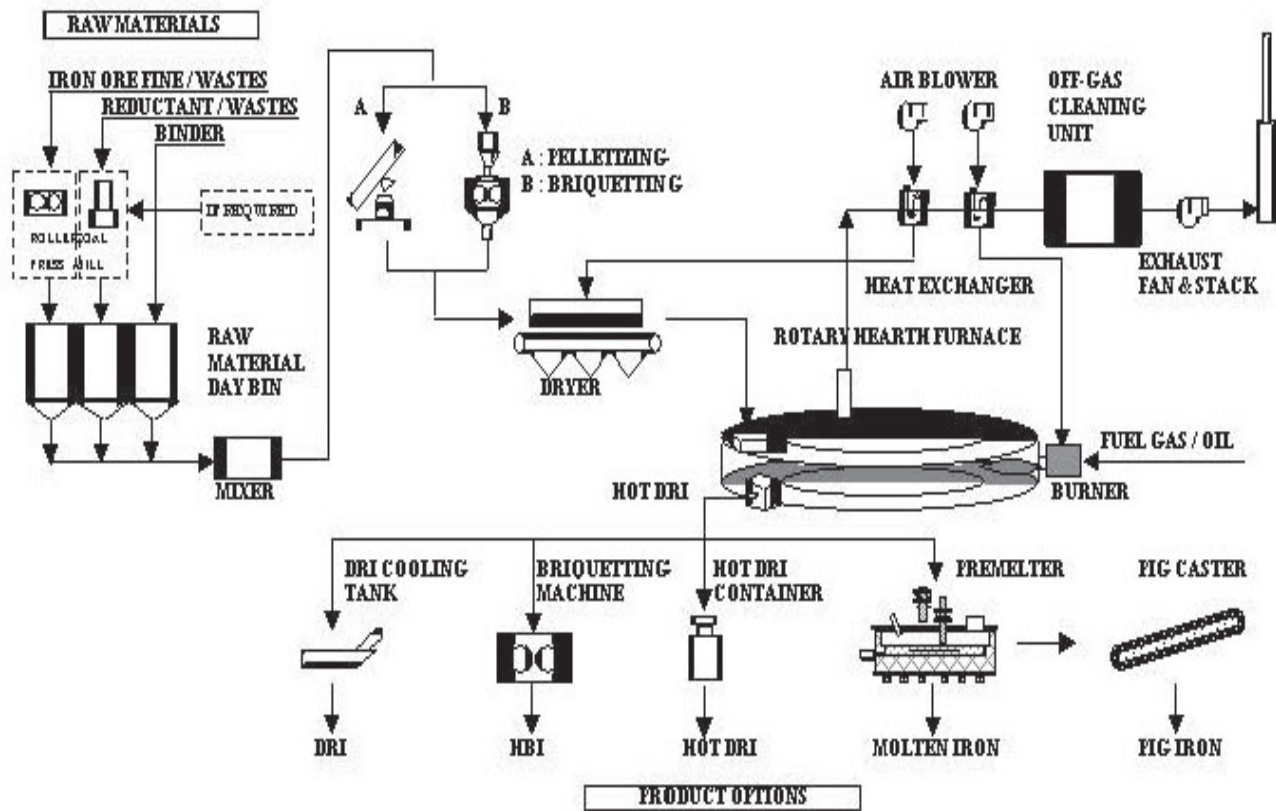
ates at ambient atmosphere where HYL reduction unit operate at high pressure (5 atm); also due to steam reforming, the reformed gas contains higher proportion of hydrogen in HYL process. Pressurised system and high hydrogen in reformed gas in HYL might be a safety concern. Another advantage of MIDREX is that it operates at comparatively low temperatures (800-900°C) compared to that required in HYL (920-1050°C). MIDREX has some limitations regarding the short life of nickel catalyst used in the reformer, and inability of using high sulphur ore due to direct uses of off-gas from reduction unit to the reformer. Although MIDREX was designed for 100% pellet, it can operate with 30-60% lumpy ore depending on the type of ore (non-decrepitating and reactive ore). The energy requirement is of the order of 10GJ/t with an efficiency of 75% marginally lower than HYL pro-

cess (89%). In India, we have several units of Midrex (six in Essar with total capacity of 5.5 Mtpa). JSW Ispat at Raigarh has one unit of 1 Mtpa. A flow sheet of MIDREX unit is shown in **Figure9**.¹³ MIDREX in association with Praxair has developed a process called MaxCOI(R), where COG can be used as reducing gas in shaft furnace. Lurgi has technology for gasifying coal bed by oxygen and steam. Recently, a 1.8 Mta MxCOI(R) unit has been set-up in Angul plant of JSPL that uses Lurgi coal gasifier to produce reducing gas to support reduction in shaft furnace. This is definitely an India-centric approach for utilising non-coking coal, available in plenty in India.

As mentioned earlier, rotary hearth furnace-based processes evolved mainly to utilise the iron-bearing solid waste from steel plants. Rotary hearth furnaces are usually gas-fired, which can be

sourced from natural gas/coke oven gas from plant. Iron ore-coal composite pellets/briquettes (sourced from off-grade ore, iron-bearing solid waste, non-coking coal fines) are used as feed and either DRI or nugget is obtained at the discharge end. Iron nugget is produced in a process called ITmk3 (ironmaking technology marked three after first generation convention BF and then second generation sponge iron processes). In such process a separate high temperature zone is maintained beyond the reduction zone for slag metal separation. However, such process has not been commercialised so far, while several commercial processes exist for producing DRI using RHF, like FASTMET(R), INMETCO processes. Since the residence time of the gas in the reactor is short and heat is transferred from furnace atmosphere to solid bed by radiation, and unlike blast fur-

Figure10: The flowsheet of FASTMET(R) process



nance, as there is no direct gas-solid heat exchange, the off-gas carries around 50% of the total input energy (17GJ/tDRI). Off-gas volume is large with calorific value (~1000 kcal/Nm³) comparable to that of BF gas.¹⁴ The off-gas, therefore, need to be utilised for power generation that can feed electricity required in the plant and subsequent melting of DRI in EAF, such that the process becomes energy-wise comparable to the BF process. Since the fuel gas in RHF is either natural gas or coke oven gas, those are rich in hydrogen, the CO₂ emission is likely to be less compared to BF, where carbon rich fuel is used. Besides, as the carbon and iron ore particles are intimately mixed in pellets/briquettes, the utilisation of reduction coal is more efficient. One of the ore recent studies indicated that actual reductant coal requirement is much below the

stoichiometric requirement (typically 20 wt% in composite pellets) for 100% direct reduction.¹⁵ Another of our recent studies on CFD (computational fluid dynamics) in the freeboard of the RHF indicated that nozzle configuration and fuel gas mixture has a role in mitigating CO₂ emission from RHF.¹⁶ The flow sheet of a commercialised FASTMET(R) process is given in Figure10.¹⁷ It may be noted here that the off-gas is extensively used for drying purpose, although not used for electricity generation.

The most important advantage of RHF-based process is that the iron bearing solid waste from the plant can be converted to value added sponge iron using a less capital intensive unit in a small land space. Since the burden does not move physically and the rotating hearth carries the material through different tem-

perature regimes, naturally cured low strength pellets/briquettes could be utilised comfortably.

Smelting reduction route

As mentioned earlier, smelting reduction routes evolved to avoid coke-making and use directly non-coking coal to produce hot metal of blast furnace quality. There are basically two types of SR processes – single-stage and two-stage. In single-stage process, iron oxide, coal, flux, and oxygen are charged in a single reactor, and oxide is reduced in liquid state only to produce liquid hot metal. Romelt and HIs melt are two such processes in this category.

Romelt is Russian technology (Figure11),¹¹ tested in pilot scale at Novolipetsk Metallurgical Kombinat (NLMK) plant, USSR. The coal and

oxygen rate in such furnace are quiet high. Coal rate ranges from 1.1-1.3 ton/thm depending on ash content and oxygen rate 1000-1100Nm³/ton. The off-gas calorific value is also quiet high at 1700Kcal/Nm³ compared to 900Kcal/Nm³ of BF gas and with lots of sensible heat associated with large volume of off-gas volume (2800Nm³/ton) at 1600°C.^{1,10} Although 70% of CO generated by coal oxidation is post combusted in the upper part of the smelting reduction vessel (SRV), the process has inherent limitation to effectively transfer the heat to the liquid load and dust laden gas emits at very high temperature at 1600°C. The process never becomes viable without utilising the off-gas for power generation and selling it after meeting the plant electricity requirement. One positive point of this process was that it generated excellent quality hot metal with very low silicon and phosphorus. Most of these elements are eliminated in the slag phase during the process. However, large consumption of coal and oxygen still remains a huge obstacle towards its commercialisation.

One of the novel single-stage SR processes that has been commercialised is the HIs melt process at POSCO steel works, Korea. The unique feature of HIs melt process is that the off-gas credit of this process is quiet low compared to other SR processes, and it does not acts as a pointer for meeting the process economics. A schematics of the process flowsheet of HIs melt process is shown in **Figure12**.¹²

Process-wise also it is unique because it uses top lancing of preheated oxygen enriched air blast, in place of room temperature pure oxygen from the bottom. Preheated air carries lot of sensible heat that reduces coal rate significantly. Presence of lots of nitrogen from air blast restricts the temperature in the vessel that improves refractory life and reduces the temperature of the off-gas. Dried iron ore fines and coal fines are injected

Figure11: Schematics of ROMELT process

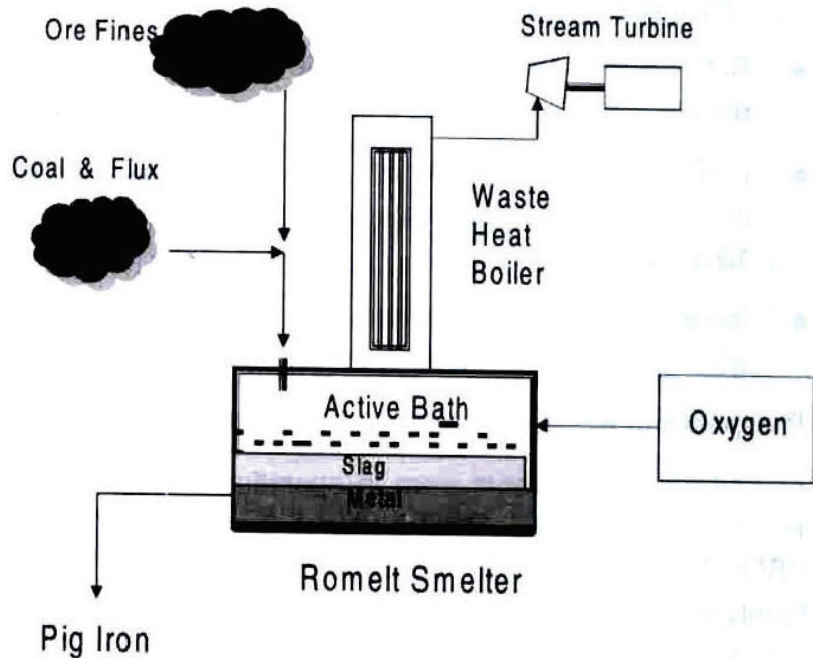
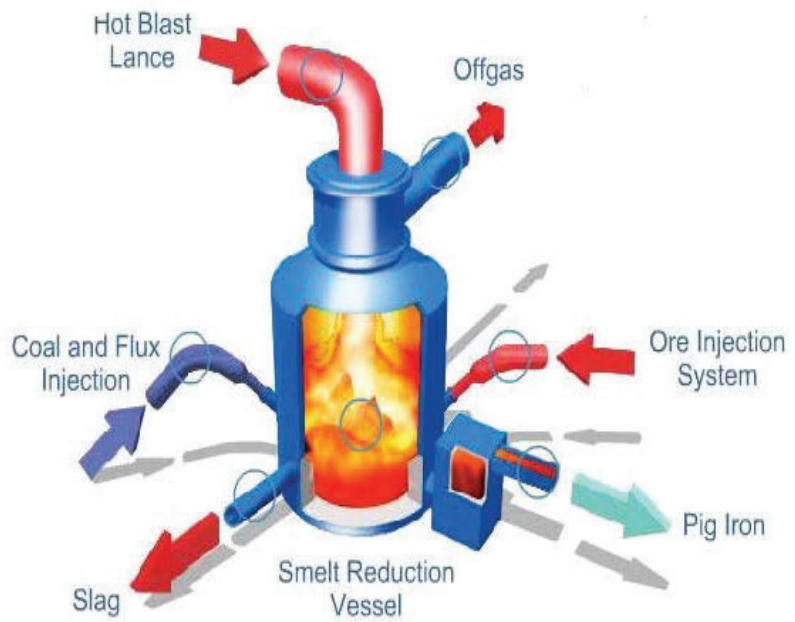


Figure12: Schematics of HIs melt process



into liquid bath that assists in easy capture and faster melting of fines in liquid. Top lancing facilitates formation of slag-metal-gas emulsion that helps in faster reaction. The cleaned off-gas from the reactor is partially used in air preheating stoves and the remaining flue gas has calorific value (700kcal/Nm³),¹ which is less than that of BF gas and just suitable for some downstream application as fuel gas. The process is also claimed as a green technology with 20% lower CO₂ emission than BF; besides it also produces much less toxic gases like SO_x and NO_x.¹ But the process is capital intensive with several ancillaries like hot blast stoves, oxygen plant, ore, coal preheating unit, powder injection assemblies, vertical lancing system etc.

The most popular SR processes are the two-stage processes like COREX(R) and FINEX(R). In COREX(R) process, first the lumpy ore along with pellets are partially reduced in a reduction unit (RU) under high pressure (4-5atm), which is subsequently charged to the second reactor called the melter-gasifier (MG). Coal and pure oxygen is charged in the MG and intense heat is generated that melts the partially reduced ore from reduction reactor and complete the rest of the reduction in the liquid state. A fraction of off-gas from MG is sent to RU after gas cleaning. The final off-gas from RU and MG after cleaning, maybe used for power generation or DRI production in a shaft furnace. A schematics of the two stage COREX process flow sheet with off-gas utilisation is given in **Figure 13**.¹⁸ If off-gas is not utilised the cost of hot metal from COREX could be 50% higher than that of BF; on the other hand if off-gas is utilised for power generation/reduction/as fuel for downstream application, the cost advantage could be 10-20% towards COREX.¹ Besides, COREX has other advantages like less toxic emission, using non-coking coal (environmentally friendly as it avoids coke ovens; secondly, reduces dependence on

Figure 13: Schematics of COREX(R) process

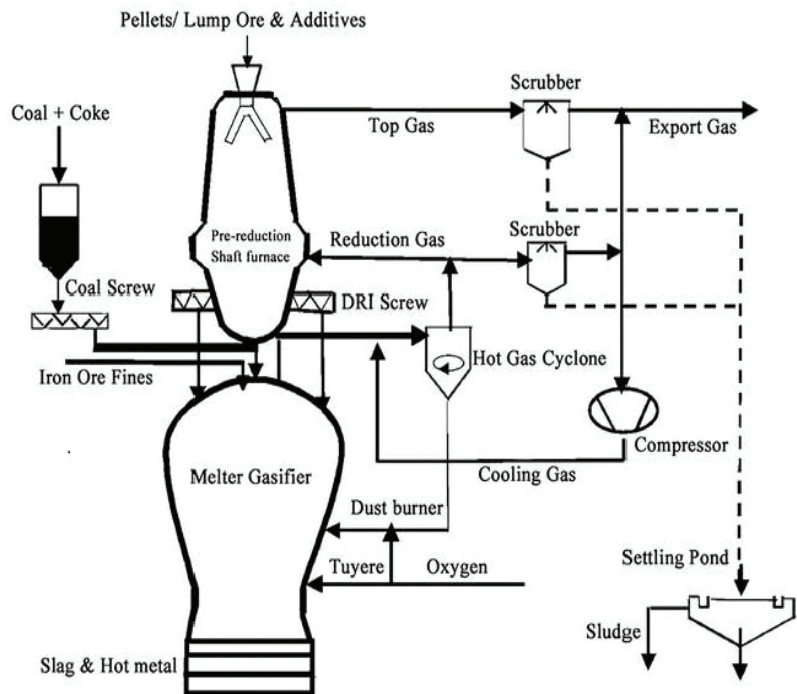
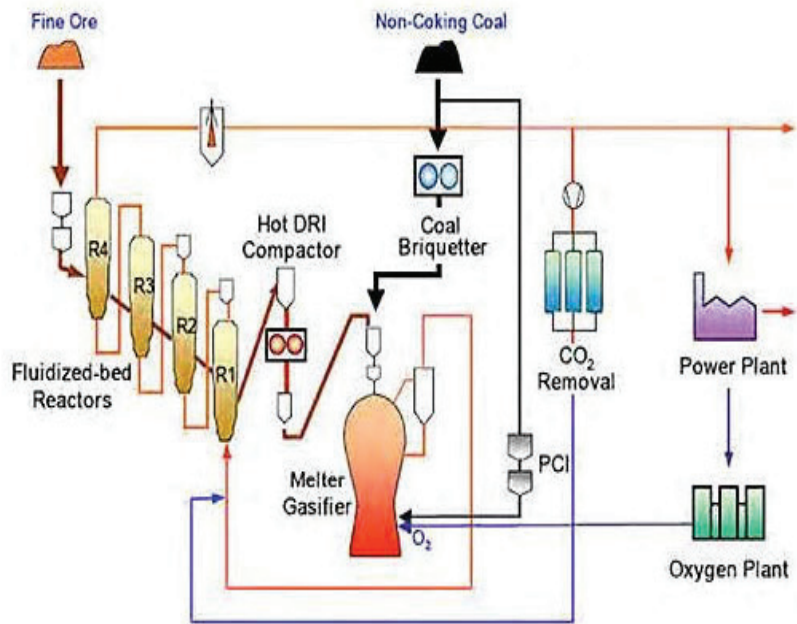


Figure 14: Schematics of FINEX(R) process

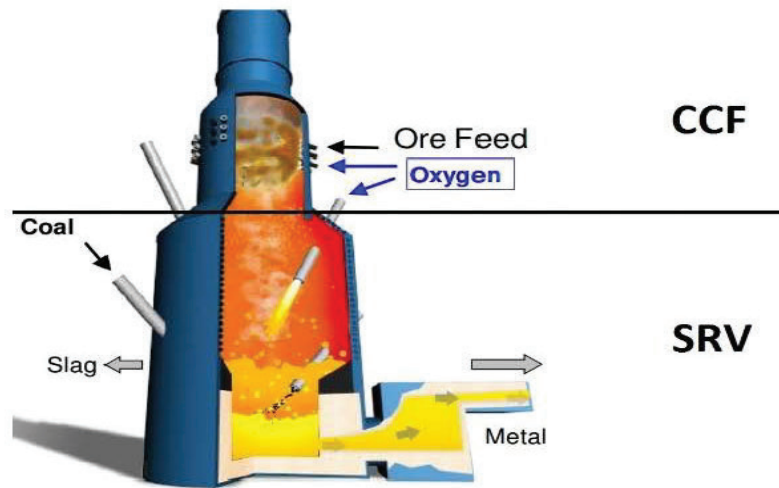


coking coal import from abroad), higher specific productivity (3-3.5t/m³/d), and it can operate at much smaller sizes (for example more popular C-2000 model operates at 2000tpd; other two variants are C-1000 and C-3000), and stopping and restarting of furnace is a matter of few hours. JSW, Vijaynagar has two C-2000 modules of COREX. JSW COREX has typical fuel rate of 1000kg/thm including 100kg of coke. Coke is used to maintain a permeable deadman coke at the bottom of MG. JSW utilise off-gas to generate power; while off-gas is used for producing DRI at Saldanh (South Africa) plant. Recently, JSW also injecting iron ore fines directly in the MG to improve the efficiency of the furnace.

FINEX(R) process was developed in Pohang, Korea to utilise the iron ore and coal fines (Figure 14).¹⁹ In this process the iron ore fines are reduced in a fluidised bed as in FINMET and then the reduced iron are hot compacted to briquettes for subsequently charging into melter-gasifier. Similarly, coal fines are dried and briquetted before charging to the MG. There is only one operating 1.5Mtpa plant in Pohang steel works in the world today. Its coal rate is quite low 750kg/thm with 30-50 kg coke. Since it can utilise cheap iron ore fines and coal fines directly, it reduces raw material cost significantly. It is claimed that 1.5 Mtpa Finex produces hot metal more effectively in terms of cost than 3 Mtpa BF, by approximately 15 to 20% lower. Emissions of SO_x, NO_x and dust are also demonstrated much lower than BF. But the inherent problem with fluidised bed reduction at high pressure still remains.

The most recent and promising SR technology is the HIsarna process jointly developed by Tata Steel, Europe and Rio Tinto. It is also a single-stage SR unit similar to HIs melt process with an additional cycle converter furnace at the neck of the bottle shape SRV unit. The schematics of the process is depicted in Figure 15.¹² Coal and oxygen is charged

Figure 15: Schematics of HIsarna process



at the bottom of SRV. Auxiliary oxygen is also charged at the top of the vessel for post combustion of CO to CO₂. Therefore, the off-gas is rich in CO₂ and easily can be sequestered. In CCF a high temperature cyclone is formed that melts the iron ore fines injected at CCF and trickles down to SRV for reduction. The capex and opex are lower than BF. The process is claimed to have 20% lower energy usage, 20% lower CO₂ emission, and even 80% lower CO₂ emission if it is sequestered.²⁰ A continuous six-month operation has been demonstrated but it is yet to be commercialised.

Conclusion

The BF-BOF route of crude steel production still holds a dominant position today. BF has undergone several developments that improved its fuel and energy efficiency. In spite of all these advancements, BF still emits around 2 ton of CO₂ per ton of iron produced. There are two potential technologies for mitigating CO₂ emission from BF. One of them is the low temperature low emission technology that aims to reduce the fuel rate by increasing the CO utilisation of indirect reduction of wustite at lower temperature and subsequently increasing

the overall thermodynamic limits of CO utilisation and further lowering the fuel rate and emission. This can be achieved by increasing coke reactivity, sinter reactivity, or using iron ore-coal composite pellets. In another approach, ULCOS top gas recycling blast furnace (TGR-BF) has been conceived, where the top gas is recycled back in the furnace after scrubbing CO₂ from off-gas. Pilot scale trial has demonstrated 20% reduction in fuel rate and 50% reduction in CO₂ emission. However, the process is also likely to reduce the downstream fuel gas from blast furnace adversely.

Blast furnace ancillaries like coke oven and sinter plant also adds to pollution; besides CO₂ emission, they also adds toxic gas to atmosphere. Another bottle neck of BF process is that to run it efficiently a minimum amount of costly coke is required. Therefore, some alternative routes (DR and SR processes) have evolved that can produce iron using non-coking coal without a coke oven and sinter plant. Direct reduction (DR) processes produce sponge iron in solid state followed by melting in electric furnace; while smelting reduction (SR) directly produces hot metal of blast furnace quality from non-coking coal. In most

of the cases smelting reduction is similar to blast furnace operation but the function of BF is divided into two separate and independent reactors connected by solid and gaseous streams externally. This makes allowances for the use of low quality cheap raw materials like non-coking coal, lumpy iron ore, iron ore fines, iron bearing solid waste from plant. But major drawbacks of smelting reduction route are high coal rate and rich off-gas, which essentially has to be utilised to make the process economical.

The two-stage COREX process appears to be the most promising among the SR processes. If the off-gas from COREX process is properly utilised for DRI reduction/or generating power, the cost of hot metal produced from COREX becomes lower than that from BF. The potential of HISRNA process towards fuel efficiency, CO₂ mitigation and capture is also very promising.

From the Indian perspective, rotary kiln-based DR process holds a promise, as it is a rugged process and India has a large reserve of non-coking coal. But, for its sustainable growth, the large volume of dust laden rich off-gas needs to be cleaned and used for power generation before it is left to the atmosphere. A separate reactor for coal gasification will make the process further cleaner and energy efficient.

Shaft furnace-based direct reduction process using coal gasified synthetic gas is another welcome approach from Indian perspective. Recently JSPL has installed 1.8Mtpa MaxCO_I^(R) unit at its Angul plant that reduces iron ore in shaft furnace using synthetic gas that is produced by gasifying low grade coal bed by steam and oxygen.

Rotary hearth furnace-based DR process with minimal capital investment has an edge of converting iron bearing solid waste to value added product; otherwise dumping such solid waste invokes environmental concerns.

Indigenisation of processes based on

Indian raw materials and conditions, are essential at this point and several such processes have also been developed, especially for rotary kiln-based DR processes like JSPL (Jindal Strip Ltd, Hissar) process, TDR (TISCO direct reduction) process, OSIL (Orissa Sponge Iron Ltd) process etc. Several such indigenous processes, especially applying out-of-the-box disruptive technology suiting the Indian raw material and conditions, is the need of the hour.

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