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Descriptive modelling of the HIsarna process

Dharm Jeet Gavel[a,*], Chris Barnes[a], Christiaan Zeilstra[a], Koen Meijer[a], Arie Hamoen[b], Johan van Boggelen[a]
a. Tata Steel in IJmuiden, The Netherlands
b. Aha-Met-Consult
*dharm.gavel@tatasteeleurope.com

Abstract

HIsarna is an innovative ironmaking technology, which pursues a significant reduction in CO_2 emissions during iron production. In the HIsarna process, coal and iron ore fines are utilised directly. Hence, coal coking and iron ore agglomeration (pellet and sinter) are not required before smelting in the HIsarna process. HIsarna consists of two main parts: the Cyclone Converter Furnace (CCF) and the Smelting Reduction Vessel (SRV). The CCF is located on the top of the SRV. The iron ore fines and oxygen are simultaneously injected into the CCF. After partial reduction and melting, the liquid ore drops into the SRV. To continue the smelting reactions, the coal fines are injected at the slag-metal interface in the SRV. For the process understanding and improving control tools, a seven zone descriptive model is developed. In the present paper, theories of the seven zones and their relationship with the HIsarna process data are discussed.

1. INTRODUCTION

Steel is required for a sustainable society. However, iron and steel production is notoriously known for its CO_2 emission. Therefore, a reduction in the CO_2 emission from the iron and steel industry is the need of the hour. Under the ULCOS (Ultra-Low CO_2 Steelmaking) program supported by the European Union, an alternative iron-making technique is developed called HIsarna [1]. HIsarna process pursues a reduction in CO_2 emission by about 80% with a carbon capture facility [1-3].

The HIsarna combines two different developments: first the smelt reduction vessel (SRV) developed by Rio Tinto (HIsmelt), and second the cyclone converter furnace (CCF) or smelt cyclone developed by Tata Steel in IJmuiden. Currently, the HIsarna process is at the pilot plant stage, which is located at Tata Steel in IJmuiden, Netherlands. Before the development of the scaled-up demonstration plant, various competence of the HIsarna process is being tested in the pilot plant. Several successful run campaigns have already been performed in the HIsarna pilot plant. A brief history is shown in Table I.

Table I. List of HIsarna campaigns [4].

Campaigns	Aim	Start Date	Milestone
Campaign A	Feasibility check of the new HIsarna process	04/2011	First liquid metal tapped (May 2011)
Campaign B	Check the process stability	10/2012	8 tons/hour design capacity was achieved
Campaign C	Sustained liquid iron production with different raw material	05/2013	First time commercial steel grade was made from HIsarna hot metal. Continuous metal produced for 2-3 days
Campaign D	Sustained metal production	05/2014	Production lasted several days
Campaign E	Sustained campaign for six months	10/2017	New facilities are installed like offgas duct, coal dryer, screening and grinding units. Steel scrap usage was tested (up to 53%)
Campaign F	Carbon capture (CO_2) integration	06/2019-continue	Biomass and steel scrap usage resulted in the reduction of CO_2 emission by 50 %

The iron ore agglomerates (pellet and sinter) and coke are not required in the HIsarna process of ironmaking. This not only results in lower CO_2 emissions but also provides significant flexibility in the selection of raw materials for ironmaking. Furthermore, various iron ores initially considered inferior due to the high phosphorus and titanium content can now be potentially handled in the HIsarna process. Additionally, for circularity various steel industry wastes (dust, sludge, and slime) are being tested for sustainable processing. Moreover, steel scraps utilisation in the HIsarna process is also being experienced to increase the circular economy.

A key advantage of the HIsarna process is that the injected iron ore particles melt almost instantaneously in the smelt cyclone. After which the chemical reactions take place between liquid-liquid and liquid-gas interface at much higher kinetics. On the other hand, in the blast furnace, the majority of chemical reactions take place between solids and gases. A schematic of the reduction route taken by iron oxide in the blast furnace and HIsarna is shown in Fig. 1.

In HIsarna, iron ore fines are pre-reduced and get molten in the CCF (Fig. 2). These molten droplets fall in the SRV for further reduction to the metal iron. To carburise the hot metal, the coal is injected by solid injection lance (SILs) at the interface of metal and slag. During the process, gangue minerals (impurities) react with the flux to form slag, which is timely tapped out from the SRV.

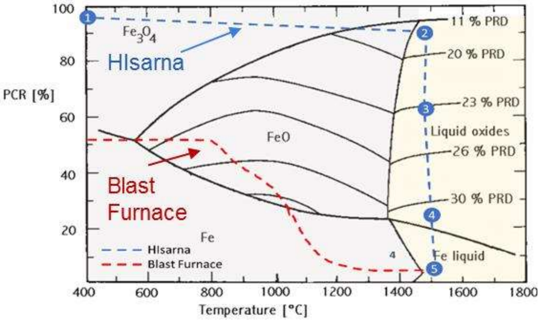

Figure 1. Schematic of the trajectory followed through the different iron and iron oxide phases for both the blast furnace (red) and HIsarna (blue).

Though HIsarna has several advantages over the blast furnace route, its process is not optimised. To optimise and improve the control of the process, an understanding of the physics, chemistry and thermodynamics of the process is required. The fundamental model is a valuable tool to combine the process with the theory.

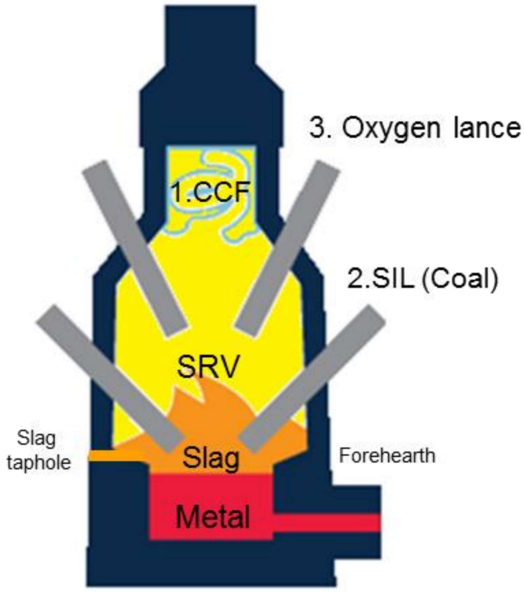

Figure 2. Schematic of the HIsarna process showing (1) ore injection in the smelt cyclone, (2) coal injection in the SRV and (3) oxygen injection in the SRV.

Furthermore, a model is necessary to extrapolate the process behaviour under the scale-up conditions. Thus, in the present paper, a descriptive model of the HIsarna process is presented.

2. SEVEN ZONE DESCRIPTIVE MODEL

HIsarna process is divided into seven zones for the process modelling purpose (Fig. 3). The reduction of molten iron ore (pre-reduced) by the carbon dissolved in the hot metal is referred as the ‘main process’ (zone 1, 2 & 3). The elements which are not used in the main process will become part of the ‘secondary process’ (4, 5 & 6). In the current model only Fe, C, O_2, N_2 and H_2 are considered. For simplicity, it is also assumed that ore complete pre-reduction to wustite (FeO) takes place in the cyclone or in the gas phase (zone 3, 4 and 7) only.

The gas from the primary and secondary processes is (partly) combusted by the SRV oxygen injection. The SRV off gas enters the smelt cyclone in zone 7, where it will reduce and melt the injected iron ore. Oxygen is also injected into the smelt cyclone to provide energy for ore melting by combusting the CO and char coming from the SRV.

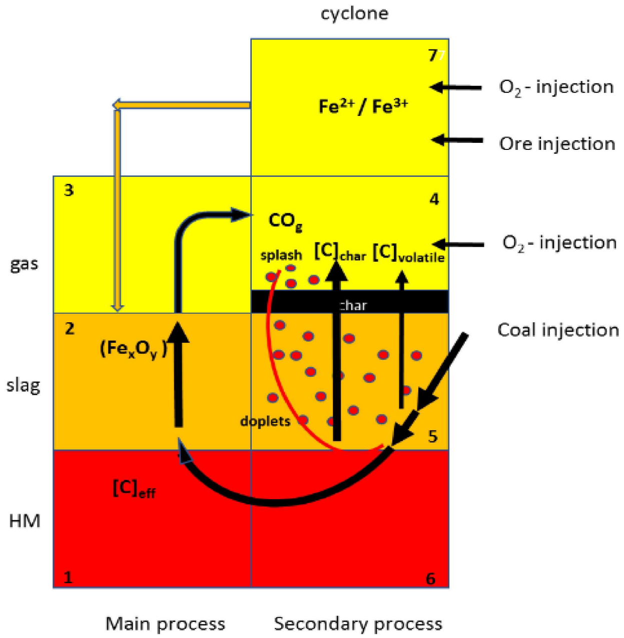

Figure 3. A schematic of the seven zone HIsarna process model.

2.1 Main Process

Zone 1 represents the liquid hot metal (Fig. 3), with a carbon content of around 4 % $[C]_{HM}$. Zone 2 represents the slag, which is continuously fed with (pre) reduced iron ore dripping from the smelt cyclone. Depending on the pre-reduction degree (PRD) at the cyclone this becomes the (Fe_xO_y)slag. The iron total from the slag (oxide) is between 3.0 % and 5.0 %. Based on this, the main reduction reaction can be described as:

$$[C]_{HM} + (FeO)_{slag} \dashrightarrow CO_g + [Fe] \qquad (1)$$

For the model, it is assumed that the main process is at a 'steady state'. This means that the hot metal carbon content ($[C]_{HM}$) and slag FeO content are constant over a longer period of time, which does not have to be at the thermodynamic equilibrium. This determines the amount of carbon (coal) required for the main reaction.

Formed metallic iron [Fe] alloys with carbon to about 4%, which will consume the injected coal. Keeping $[C]_{HM}$ steady and alloying the produced [Fe] to the HM levels represent the minimum amount of carbon injection for the main process of HIsarna. Considering a PRD of 33.3% and an $[C]_{HM}$ of 4% this means a minimum carbon equivalent of 245 kg $[C]_{main}$/t HM. In this estimation, the heat balance or energy need is not taken into account. When the carbon content of the injected coal is assumed to be 75%, the minimum coal injection needed for the main process becomes 327 kg coal/t HM.

The energy required for this process is generated above the slag layer. This energy requirement will be compensated by the post-combustion and mixing in zone 4, which is described in the next section.

2.2. Secondary process

Carbon not consumed in the main process passes through the slag layer (Fig. 3). In the model, this is allocated to the secondary process (zone 4, 5 & 6). Part of the carbon in the coal is bound in the volatile matter. It is assumed that the volatile carbon never reaches the hot metal surface but rises through the slag in the gaseous form. In the model, this carbon ($[C]_{volatile}$) reports to the gas phase in zone 4 (Fig. 3).

The lance angle is chosen for mixing and temperature control purposes but it limits the penetration depth. A limited penetration depth could mean that the injected solid carbon particles don't have enough time to dissolve into the liquid hot metal. These particles will float to the surface of the hot metal bath and eventually even float to the surface of the slag. These carbon particles won't take part in the main process and thus become part of the secondary process. This carbon will be called 'char' or $[C]_{char}$. The amount of char is defined by the following equation:

$$[C]_{char} = [C]_{injected} - [C]_{main} - [C]_{volatile} \qquad (2)$$

The different chars have in common that they are non-wetting with slag [5]. Therefore, it is assumed that the char, which is not dissolved in the hot metal will not react with the slag. Char will report to the gas, in zone 4, as solid carbon particles.

Based on selected coal injection parameters, there is a substantial amount of the metal droplets freed from hot metal surface. These droplets are either suspended in the slag or splash out of the slag, into the top space of the SRV. Variations in the size and number of the droplets, as well as whether they stay suspended in the slag, or exit the slag and enter the gas phase directly can affect the steady state and possibly cause major process deviations. Thus, these metal droplets and splash are considered in zones 4 and 5 of the secondary process.

The hot metal droplets that stay suspended in the slag will be called 'droplets'. This has similarities with metal droplets suspended in slag in basic oxygen steelmaking as described extensively in the literature [6-8]. Unlike the carbon particles, hot metal droplets will react intensely with the slag (perhaps bloat also). This reaction is similar to the 'main process' reaction that occurs between metal and slag at the interface. However, considering a potentially large influence on the deviation from the steady state conditions, this reaction is accounted for in the 'secondary process'. In the work, deviation from the steady state condition is not discussed.

If the droplets are freed from the hot metal surface with a high impact, they can leave the slag altogether and enter the gas atmosphere of the SRV. This will be called 'splash' in terms of the current model. Metal splash returning from the hot gas atmosphere to the bath will enhance the heat transfer from the hot gas to the hot metal bath.

3. MODELLING

The flow sheeting model for IRon MAking (IRMA) [9] is used to calculate the chemical equilibrium in zone 4. The IRMA utilises the thermodynamic data of Factsage through the ChemApp DLL. The zone 3 and 5 form the main input for zone 4. Because the main components in these zones are gaseous and the temperatures are high, it is assumed that equilibrium conditions will be met. The oxygen injection is added to this zone as well. The equilibrium calculation is an isothermal calculation, which means the temperature in zone 4 is set to a fixed value. The input for the model in zone 4 is the CO bath gas of the main reaction from zone 3. The $[C]_{volatile}$ and $[C]_{char}$ from zone 5 will enter zone 4, as will the conveying and booster gas (nitrogen) that came with the coal injection. Furthermore, the hydrogen and the moisture of the injected coal were used in calculating the gas amount and composition.

4. RESULTS

There are four important control parameters for the SRV and smelt cyclone. These are the injection of coal and oxygen in the SRV and the injection of ore and oxygen in the smelt cyclone (Fig. 2). By adjusting these four parameters at least two conditions have to be established: 1) a steady state of the main process and 2) an optimised energy balance for the ore injection section.

4.1. Steady state

A steady state is defined as the stability of the carbon content in the hot metal and the FeO content of the slag. In Fig. 4, the carbon content of the hot metal and the FeO in the slag for run F3.2 is shown. Assuming an iron ore PRD of 33.3% means that the analysed *Fe-total of the slag is plotted as FeO. By evaluating the average values and the standard deviation (1 σ) of the samples, this run is considered to be at a steady state:

Average $[C]_{HM}$ = 4.12 +/- 0.14% (305 samples).
Average $(\text{Fe-total})_{slag}$ = 3.42 +/- 0.37% (183 samples).

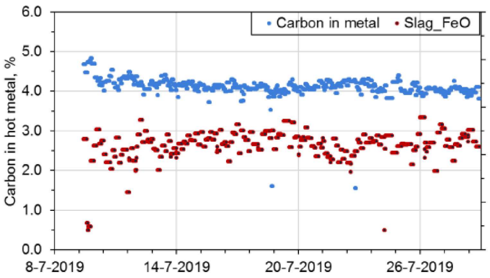

Figure 4. Concentration of hot metal carbon and slag FeO for the HIsarna run F3.2.

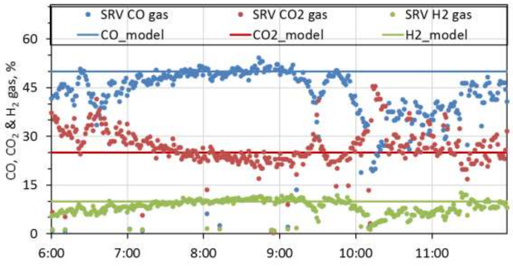

Figure 5. Example period of SRV gas analysis with the model predicted values, whilst the process control parameters are not changed.

4.2 SRV gas analysis

In the example of run F3.2, for a 5-hour period both the coal and SRV oxygen injection rate has been constant (Fig. 5). The readings show that this does not result in constant gas composition. Right at the start of the graph and just before the CO_2 peak near the end of the period in this graph, the CO percentage is around 50%, CO_2 around 25% and the H2 around 10%.

When the Mixer Model in IRMA is fed with the actual injection data the outcome matches the periods with 50% CO, 25% CO_2 and 10% H_2. Since the setpoints did not change for the periods with lower CO and H_2 and higher CO_2 the model cannot account for these situations. A lower percentage of CO and H_2, and a higher percentage of CO_2 could be reached in 2 ways: an oxygen level in the SRV top space that is higher than calculated in the model or a lower carbon level in the slag (char) and hot metal.

If the PRD in the smelt cyclone is very low, but the PRD in the slag is always 30% or more, extra oxygen can become available in the SRV top space. The extent of this is difficult to assess, as the extent and rate of these PRD fluctuations in the smelt cyclone are still unknown.

Depending on the equilibrium conditions in the SRV top space char can remain, or reform, depending on the local CO, CO_2 and O_2 concentrations and temperature. Char in the SRV can remain in the SRV waiting for oxygen. While waiting there is a chance that the char is tapped with the slag during a slag tap. This carbon is lost in the process. When slag is being tapped char can be observed in slag. The amount of char observed can vary quite substantially, although no actual quantification is available. Another possibility is that the char will detach from the slag and is carried with the SRV off gas flow to zone 7, the smelt cyclone. This is also a carbon loss for the process, which results in a loss of process efficiency.

Furthermore, another reason for the deviation can be an inhomogeneous gas mixture in the SRV top space. In front of the oxygen lance in the SRV, a local oxygen-rich regime might be developed, which has to be compensated by regions with an oxygen shortage. From a process control and stability perspective, this is not a favoured situation. A homogeneous gas atmosphere is preferable and will bring the actual SRV gas area closer to the theoretical zone 4 situation of the Mixer Model, which assumes a homogeneous gas mixture.

A key objective in the process control strategy is to work towards a zero unreacted char in the SRV. This means there should be no char losses from the SRV to the cyclone or off-gas, but that it is all consumed in the SRV or the lower section of the smelt cyclone, where it is most effective. This should stabilise the SRV gas composition.

When the conditions in zone 4 are understood and well controlled, the injection section of the smelt cyclone, zone 7 in the model, can be optimised.

5. CONCLUSION

For the HIsarna process, limited scientific data and literature are available. Every new pilot plant sprint with a variety of trials provides immense understanding and potential of the HIsarna ironmaking process.

Based on the process background and available plant data, a seven zone descriptive model for the HIsarna process is developed. The seven zone HIsarna model theoretically illustrates the process in two parts. The first part is called the 'main process', which consists of the hot metal (zone 1), slag (zone 2) and evolved gas (zone 3) through the main reaction (equation 1).

The second part is called the 'secondary process', which consists of surplus carbon in metal (zone 6), a metal droplet in the slag layer (zone 5), metal splash and coal as char and volatiles above the slag layer (zone 4), the process gas from SRV and smelt cyclone at top space (zone 7).

The seven zone HIsarna model will be a useful tool for the HIsarna process prediction and control. However, it has a few limitations which are its assumption of homogeneous gas composition and the consumption of the char in the SRV. In reality at HIsarna, some char can leave the process to report as dust and the process can deviate from the steady state with falling accretion, ore/coal over and under feed, changing slag metal inventory, etc. Thus, before exploring the full potential of the model further tuning is required for such variations.

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