

RESEARCH ON THE REDUCTION OF THE CO₂ FOOTPRINT BY APPLYING NEW METALLURGICAL TECHNOLOGIES "DE:KARB"

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REZUMAT. Principala acțiune de realizare a decarbonizării atmosferei este noua noastră tehnologie „de:karb”, de prelucrare primară a cocsului-furnalului, de producere a aliajelor feroase, deoarece aici se generează emisiile majore de CO₂. Dacă fluxul tehnologic actual al furnalului este înlocuit cu tehnologia de reducere directă, producând fier spongios (Direct Reduced Iron - DRI), amprenta de carbon . DRI este propusă ca o soluție tehnologică superioară, mai ales că hidrogenul-purum ar putea fi folosit ca agent reducător, dacă este disponibil la un preț convenabil. O caracteristică specială a „de:karb” este reducerea gazelor cu efect de seră.

Cuvinte cheie: CO₂,decarbonizare, DRI, amprenta-C, EAF.

technology, of primary coke-furnal processing, of the production of ferrous alloys, because this is where the major CO₂ emissions are generated. If the current process flow of the blast furnace is replaced by direct reduction technology, producing sponge iron (Direct Reduced Iron - DRI), the carbon footprint . DRI is proposed as a superior technological solution, especially since hydrogenum-purum could be used as a reducing agent, if it is available at a convenient price. A special feature of "de:karb" is the reduction of greenhouse gases.

Keywords: CO₂, decarbonization, DRI, C-footprint, EAF.

1. INTRODUCTION

Today's integrated steel mills, which produce steel from iron ore, account for 70% of global steel production, but release nearly 90% of CO₂ due to high CO₂ exhaust, (eg 2.3 tons of CO₂ per ton of steel produced). Modern *Mini-Mills* which use electric arc furnace (EAF) technology, based on remelted steel waste (scrap), produce the remaining 30% of global steel production, and approx. 10% harmful CO₂ emissions. The application of the new Mini-Mills & EAF technology favors the emission of 0.6 tons of CO₂ for one ton of steel produced. The carbon footprint in the world's largest steel-producing countries, China=2.3 and India=2.6, is defining for the toxicity of the atmosphere. Steel production in the EU shows low values. Carbon footprint in Germany and France, with a production of approx. 70% of the amount of EU steel, is on average 1.8-1.9. In Italy and Spain the carbon footprint is lower by 20-30. % compared to Asian countries. The main action to achieve the decarbonization of the atmosphere is the our new "*de:karb*" technology, of primary coke-furnal processing, of the production of ferrous alloys, because this is where the major CO₂ emissions are generated. If the current process flow of the blast furnace is replaced by direct reduction technology, producing sponge iron (*Direct Reduced Iron - DRI*), the carbon footprint would decrease from 2.3 to 1.6

using natural gas as a reducer. DRI is proposed as a superior technological solution, especially since *hydrogenum-purum* could be used as a reducing agent, if it is available at a convenient price. A special feature of "*de:karb*" is the reduction of greenhouse gases by optimizing the technological and value flow. Artificial intelligence (AI), Digital 4.0 processes and machine learning (ML) methods play a central role in the application.





2. CARBON FOOTPRINT AS FACTOR

Carbon footprint, also called CO₂ footprint, represents the total emissions of greenhouse gases that an organization, event, product or person produces in a certain period of time. Greenhouse gases generically called CO₂ emissions, are the results of the various activities that man undertakes as a result of development and progress: transport, fuel consumption, food, manufactured products materials, wood, roads, buildings, services, etc. The carbon footprint can be calculated both at the household or individual level, as well as at the level of events (team-building, conferences, forums shows, etc.), airplane flights or at the level of a business - company or organization. I propose the calculation of the carbon footprint of an economic unit, as well as the compensation of CO₂ emissions generated by

industrial activities. I also propose to neutralize the carbon footprint through AI. EAF based steel plants were put into operation and fed fully or predominantly with DRI from a next-door unit. Plants were located in countries like Venezuela, which also had local iron ore and cheap hydro power, Mexico, Malaysia, and, particularly, in West Asia and North Africa. Iran is today the world's leading DRI producing country using natural gas reduction, producing around 35 Mt in 2024. The DRI from MIDREX and ENERGIRON SFs can be fed into EAFs for steelmaking or transported as products

3. TECHNOLOGICALLY PROCESSES

Hydrogen injection in BFs, shaft furnaces (SFs), fluidized beds, and flash ironmaking reactors are four hydrogen ironmaking technologies in development, as illustrated in **Figure 1**. Hydrogen-rich BFs can reuse the existing BF reactors, thereby reducing equipment costs. However, the use of coke as the skeleton to maintain the permeability of burden is inevitable, which limits deep decarbonization. Furthermore, partial coke replacement with hydrogen may decrease the bed permeability. A heat supply issue may arise owing to the missing internal heat source from coke and the endothermic reduction with hydrogen.

Hydrogen-based improvement and technologies			
Blast Furnace	Shaft Furnace	Fluidized Bed	Flash Ironmaking
			
Reuse existing equipment Use of coke Use of pellet/lump ore Diffusion dominated Low bed permeability Heat supply issue	Furnace design & scallop Coke-free Use of pellet/lump ore Diffusion dominated Low bed permeability Heat supply issue	Furnace design & scallop Coke-free Use of fine powders Reaction/diffusion dominated Good gas-solid contact Excellent heat transfer	Furnace design & scallop Coke-free Use of fine powders, fast reduction rate Reaction dominated Good gas-solid contact Excellent heat transfer

Blue: prest; Red: cons

Figure 1. Four sustainable ironmaking technologies in development.

4. DRI PRODUCTION

Most of the DRI production was established in **Figure 2**, where there was a need for steel production, however, with no or very limited availability of local scrap but a cheap costs .

Hydrogen injection in *blast-furnace (BFs)*, *shaft furnaces (SFs)*, fluidized beds, and flash ironmaking reactors are four hydrogen ironmaking technologies in development, **Figure 1**.

As shown in **Figure 3**, iron ore reduction with H₂ and CO is endothermic at almost all possible

operating temperatures in the SFs when H₂/CO > 1. As the H₂ content increases, the heat supply issue becomes more significant. An inadequate heat supply decreases the reduction performance, such as the reduction degree (or output) and gas utilization rate. The laboratory-scale SFs used in the experimental studies were limited in size, e.g., a diameter of 0.27 m, and measuring the temperature along the axis was possible. However, for an industrial-scale SF, e.g., 4–5 m in diameter, measuring the heterogeneous temperature field in furnaces owing to the endothermic reaction and the obstruction of kinetic and thermal transfers from the reducing gas by densely packed ores is difficult.

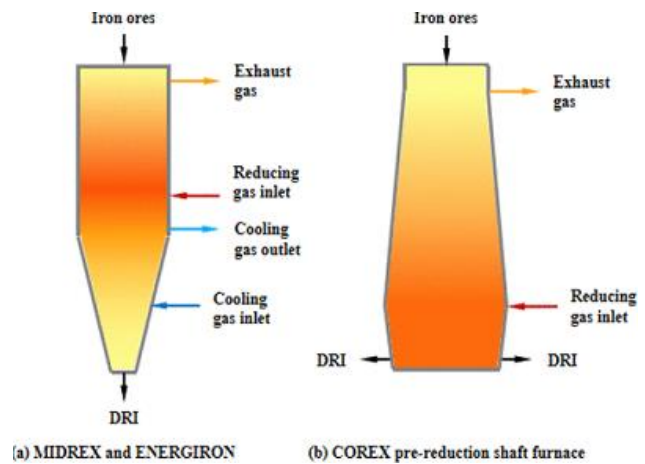


Figure 2. Profiles of main shaft furnaces

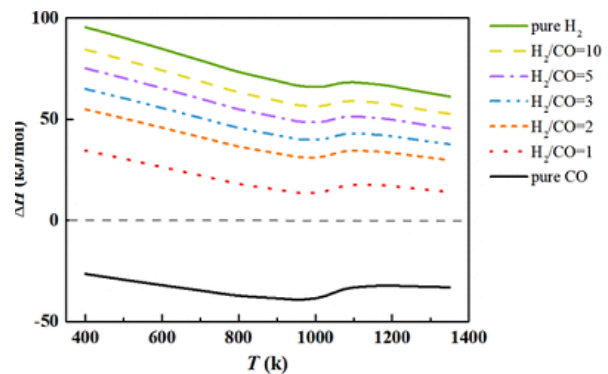


Figure 3. Reaction heat for Fe₂O₃ → Fe at various H₂/CO values. The original data is referred from the NIST Chemistry WebBook

5. PHYSICAL MODELLING

As illustrated in **Figure 4**, the multiscale physics involves gas convection and diffusion among ores, heat competition, gas diffusion in pellets, chemical reactions between the reducing gas and grains constituting the pellet, pellet sticking (by iron whiskers and solid diffusion) and degradation grain sticking (by sintering), microstructure evolution of

pellets, and lattice change of solid atoms. These physical phenomena interact with each other. For instance, pellet agglomeration could form blind and overheated zones in the bed; grain sticking could resist the reducing gas diffusion into pellets and react with grains; and the microstructure evolution of pellets could affect the reaction kinetics. Currently, no single physical model can resolve these complex multiscale physics.

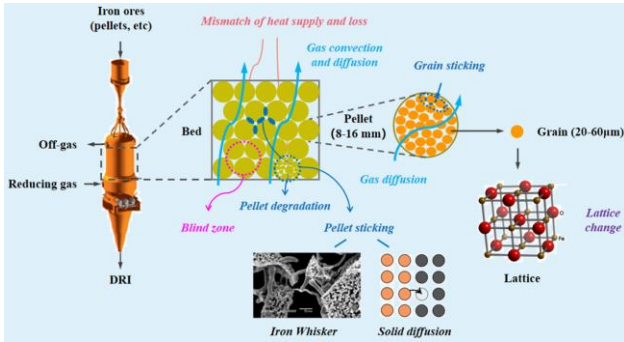


Figure 4. Multiscale physics in shaft furnaces

6. REACTION MODELS

As shown in Figure 5a, in the one-interface USCM, a series of reduction steps, $Fe_2O_3 \rightarrow Fe_3O_4$, $Fe_3O_4 \rightarrow FeO$, and $FeO \rightarrow Fe$, are performed in order. Only one reaction occurs at each stage based on the reduction degree ($f \leq 1/9$: $Fe_2O_3 \rightarrow Fe_3O_4$, $1/9 < f \leq 1/3$: $Fe_3O_4 \rightarrow FeO$, and $f > 1/3$: $FeO \rightarrow Fe$). The one-interface USCM has been widely implemented in the simulation of blast furnaces

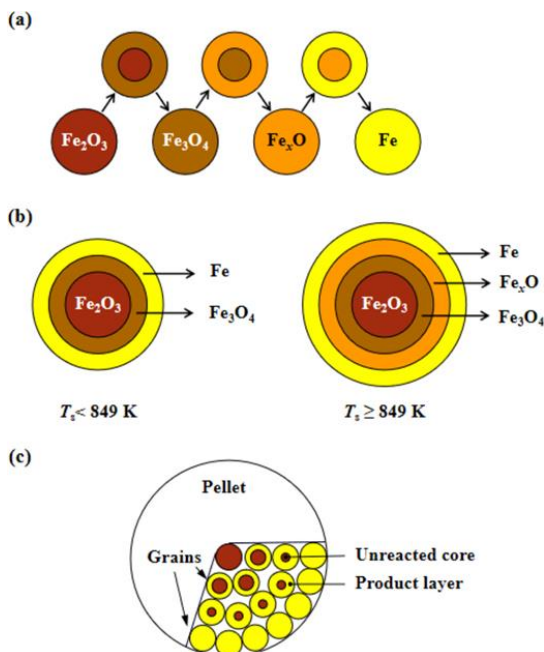


Figure 5. Three common gas–solid chemical reaction models: (a) one-interface unreacted shrinking core model, (b) multi-interface unreacted shrinking core model, and (c) grain model.

7. RESULTS

Hydrogen Plasma Reduction-(HPR). HPR offers a viable alternative for carbon-neutral iron making. Its high energy and enhanced density of H radicals and excited states help to overcome the reaction's activation barrier and has the potential for enhancing the Fe_xO reduction rates by an order of magnitude, enabling iron conversion to reach commercially viable rates. HPR-hydrogen plasma-based reduction allows the production of liquid iron in one single step, in which the input fine ores are melted and reduced simultaneously without the need for intermediate agglomeration or refinement processing, as the melting point of iron oxide ($1565\text{ }^\circ\text{C}$) only slightly exceeds that of iron ($1538\text{ }^\circ\text{C}$). Plasma discharges are generated by electric arcs in conventional EAFs to melt steel scraps. Thus, it is conceivable that established industrial electric furnaces can be modified to be used for HPR purposes, with only small (e.g. 5–10%) H_2 partial pressure. The ore can be melted and reduced by hydrogen in both molecular and plasma states. The latter is composed of vibrational ionized (H^+ , H_2^+ and H_3^+), excited (H^*) and atomized (H) species, which are formed through the mutual elastic and inelastic collisions of hydrogen particles with electrons. Under such conditions, the corresponding degree of hydrogen dissociation is determined by the competing ionization (e.g. $e^- + H_2 \rightarrow H_2^+ + 2e^-$) and recombination (e.g. $H^+ + e^- \rightarrow H$) events.

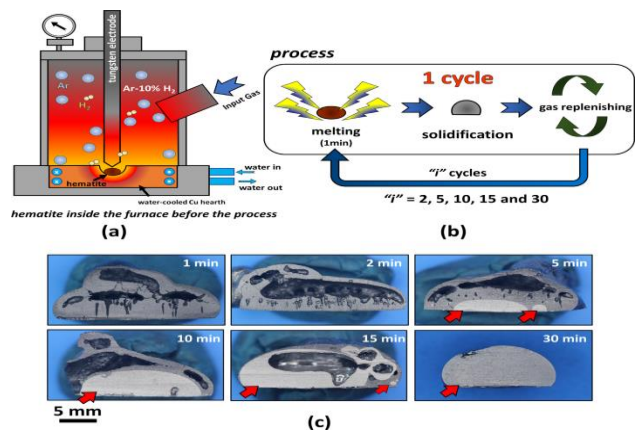


Figure 6. HPR-(a) Schematic (a)-illustration of the arc melting furnace equipped with a tungsten electrode and charged with Ar-10% H_2 gas mixture. The input hematite is placed on the water-cooled copper hearth inside the furnace before the reduction

process. (b) Sequential steps for the reduction process. (c) Hematite pieces reduced with hydrogen plasma under different plasma exposure times: 1 min; 2 min; 5 min; 10 min; 15 min and 30 min. The red arrows indicate the presence of mm-scale transformed iron in the bottom of the samples. The upper part of the samples corresponds to the untransformed remaining oxide portion.

8. CONCLUSIONS

1. ECOLOGIC ACTION (EA): Using the EA, the plant owner can save electrical energy in defined operating situations for large power consumers (such as pump and compressor drives). Power consumers can be switched off in a targeted manner, thus saving between 3-9% of energy costs.

2. *FINALLY*: The Industry 4.0 integration, communication, and usage of *AI & data*.

"Integration" means that everything in a production cell communicates with one location for data storage. *"Communication"* means linking process equipment with a computer, to learn when something is about to happen; or, establishing an open channel with a supplier, to "talk" to the equipment, and send daily or weekly reports on what is happening; *"Utilization"* means applying data to improve a process and monitor its success and failures. All this takes a systems integrator 4.0.

3. The iron conversion kinetics is dependent on the balance between the initial hematite mass and the arc power. The reduction kinetics of the 9 g hematite specimens is relative sluggish during the final 25% of reduction. *The kinetics of this process is not well understood, particularly during the wüstite reduction*

step, which is nearly an order of magnitude slower than the hematite reduction

4. The reduction rate of hydrogen plasma-based reduction, using only a small H₂ partial pressure of 10%, is comparable with those ones observed in solid-state direct reduction of hematite conducted at temperatures currently employed in shaft furnaces (850–1000 °C)..

5. So, *"de:karb" technology*, the crystals elements of the *hematite* are gradually removed during reduction, due to their high vapor pressure. Silicon enrichment was identified in the *inter-dendritic fayalite*, at the *wüstite /bcc-iron* hetero-interfaces and in the oxide particles inside iron. Since silicon oxide reduction is not readily feasible, it is majorly evaporated in the form of SiO gas. P-Phosphorus and S-sulfur concentrations were also remarkably reduced from 5 min onwards and the final obtained iron is nearly free of composite elements.

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