Modelling of an Iron Ore Reduction Furnace Operated with Pure Hydrogen

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Steel Production

- Steel production (1950) \(\Rightarrow \approx 200\) million tons worldwide\[^1\]
- Steel production (2007) \(\Rightarrow \approx 1.3\) billion tons worldwide\[^1\]
- Steel consumption (2015) \(\Rightarrow \approx 1.8\) billion tons\[^2\]
  - future growth: 3-5\%\[^1\]
  - 8-10\% growth in BRIC countries (Brazil, Russia, India, China) \[^1\] \(\Rightarrow\) dynamic expansion of their economies and infrastructures.

- Steel
  - Environment friendly material
    - can be recycled indefinitely
    - no loss of quality.
    - 40\% of steel produced is recycled from scrap
  - Use in durable products/infrastructure
    - not enough scrap available.

\[^1\] International Iron and Steel Institute (IISI): [www.worldsteel.org](http://www.worldsteel.org)

\[^2\] ULCOS Project website: [www.ulcos.org](http://www.ulcos.org)
Ironmaking today – Blast Furnace (BF)

Coke Plant: Coal → Coke

Power Plant: BF Off gases → Steam/Electricity

Pellet / Sinter Plant
Raw ore → heat treatments/additives → Sinter/pellets (better properties)

BF Off gases (CO₂/CO/H₂/N₂)

BF followed by BOF and CC
↓
1850 kg CO₂/t steel

Molten BOF and CC
↓
1850 kg CO₂/t steel

Pellet / Sinter Plant
Raw ore → heat treatments/additives → Sinter/pellets (better properties)

Coke + Sinter

BF Off gases

Pre-heated air injection

≈1500°C

Molten ore+Coke

Slag

Pig Iron

INTERNATIONAL WORKSHOP
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Steel: the Essential Numbers

World steel industry today (2008)[1]

- 1.3 billion tonnes of steel
- 1.9 ton CO₂/ton steel
- 2.2 billion tonnes of CO₂
- 4 to 5% of total man-made greenhouse gases

CO₂ Emissions x Climate Change

- CO₂ Emissions ⇒ Climate Change ⇒ Natural disasters

- The best European steel plants are operating at the limits of what is presently technically possible.

- Breakthrough technologies for steelmaking industry
ULCOS (Ultra Low CO₂ Steelmaking) Project

- **Aim:** design new steelmaking processes able to reduce by more than 50% the CO₂ emissions of the steel industry as compared to the current benchmark route (integrated plant, BF-CC)

- Launched by the major European steel companies at Sep/04

- Supported by European Commission

- 48 partners, 59 M€ budget, 5-year duration
ULCOS Breakthrough Technologies

- Optimization of the blast furnace + CCS
- New smelting technologies
  - Hydrogen steelmaking
  - Electrolysis + nuclear power

- Hydrogen-based route defined

Low CO₂ Emissions: from 200 to 400 kg CO₂/t steel
Using hydrogen for ironmaking

- Usual NG-based direct reduction “MIDREX” process

\[ \text{CO}_2 \quad \text{CH}_4 \quad \text{CO} + \text{H}_2 \quad \text{Fe}_2\text{O}_3 \quad \text{Fe} \]
Using hydrogen for ironmaking

- Pure-\( \text{H}_2 \)-based direct reduction process

  - Produces \( \text{H}_2\text{O} \) instead of \( \text{CO}_2 \)
  - Reduction with \( \text{H}_2 \) at least twice faster than with \( \text{CO} \)
Major unknowns ⇒ future price of \( H_2 \) and the \( CO_2 \) cost of the \( H_2 \) generation (electricity).

In the 2020’s \( H_2 \)-economy may emerge, as a result of the evolution of transportation and energy industries.

In this event, steelmakers should be ready to make massive use of \( H_2 \).
Aim:

- Check the technical feasibility of hydrogen ironmaking and its performance from modelling work:
  - Thermogravimetric experiments and sample characterizations to better understand the kinetic of the reactions
  - Development of a pellet-scale kinetic model
  - Development of a 2D numerical model of the reactor
  - Study of the sticking phenomenon
Main technical problems to be solved

\[
\text{Fe}_2\text{O}_3 + 3\text{H}_2 \leftrightarrow 2\text{Fe} + 3\text{H}_2\text{O}
\]

3 steps

\[
\begin{align*}
3 \text{Fe}_2\text{O}_3 + \text{H}_2 & \leftrightarrow 2 \text{Fe}_3\text{O}_4 + \text{H}_2\text{O} \\
\text{Fe}_3\text{O}_4 + \text{H}_2 & \leftrightarrow 3 \text{FeO} + \text{H}_2\text{O} \\
\text{FeO} + \text{H}_2 & \leftrightarrow \text{Fe} + \text{H}_2\text{O}
\end{align*}
\]

Influence of the temperature on the reaction rate varies significantly with the raw material

- Optimum at 800 °C
- Minimum at 950 °C

Fe

\[
\text{Fe}_2\text{O}_3
\]

3 FeO + H2 ↔ Fe + H2O

Influence of the temperature on the reaction rate varies significantly with the raw material:

- Pellets
  - Optimum at 800 °C
  - Minimum at 950 °C

- Small cubes
  - Optimum at 800 °C
  - Minimum at 950 °C

Hematite Cubes (CVKU: ap = 5 mm; mp = 550 - 5/5 mm)

200 mL/min of gas flow (H2:He 60/40)
Main technical problems to be solved

Sticking Phenomenon

- $\text{H}_2$ reduction of DR grade pellets is faster at high temperatures.
- High temperatures seem to favour the “sticking”:
  - Reduced iron pellets stick to each other with a noticeable force.
  - Hinder or block the solid flow in shaft furnaces (MIDREX, HYL).
  - Lead to a complete defluidization of fluidized beds (FINMET).
Morphological changes

- Dense grains in hematite
- Grains become porous in magnetite and wustite
- Wustite grains break up into crystallites
- Molten-like structure of iron
Kinetic model of a single pellet

- 3 reactions, mass transport (external transfer, inter- and intra-grain gas diffusion, solid diffusion, sintering of the iron layer)

D. Wagner’s PhD (2008)
Numerical model of the H₂ shaft

- 2-D, axisymmetrical, steady-state model
- Written from scratch in FORTRAN 90 using the finite volume method
- Description of gas and solid flows, mass transfer, heat transfer, 3 reduction reactions
- Single-pellet sub-model included, with kinetics derived from thermogravimetry experiments
**Numerical model of the H₂ shaft**

D. Wagner’s PhD (2008)

- **Main results**
  - Reaction with H₂ is faster than that with CO
  - Possible to use a more compact reactor than MIDREX and HYL shafts (e.g. 4.5 m instead of 9 m, with almost 100 % Fe⁰)
  - Decreasing the pellet size clearly accelerates the process
Making steel using H$_2$ as a reducing gas makes sense:

- More than 50% reduction in CO$_2$ emission by several routes
- Most of the technologies are mature
- Social acceptability can be expected
- Scientific problems are being studied

The main issues lie outside the steelmaking sector and expertise

- the future (2020, 2050) cost of hydrogen, which mostly depends on transport and energy policies
- the CO$_2$-cost of electricity.