Solar metallurgy of iron with carbon-free or bio-sourced reducers

Laboratories and groups:

- LPCNO (Laboratoire de Physique et Chimie des Nano-Objets) Lab, "Nanostructures and organometallic chemistry" and "Nanomagnetism" groups, Toulouse.
- PROMES (Procédés et Matériaux pour l'Energie Solaire) Lab, "High-temperature materials and solar fuels" group, Odeillo.
- LISBP (Laboratoire d'Ingénierie des Systèmes Biologiques et des Procédés) Lab, "Sustainable processes" group, Toulouse.

Global context

It is necessary to develop alternative processes to the ones that depend on fossil fuels, since the latter significantly contribute to global warming and are in no case long-term technological solutions for our societies, because of their inevitable exhaustion. The main source of renewable and abundant energy is the sun whose solar irradiance conversion must be optimized while minimizing the environmental and social impacts of the technologies used for this purpose. Several approaches for the use of solar energy can be considered but we want to focus on the direct use of the latter, when available, to manufacture a material or a chemical of interest: this approach minimizes the intermediate steps and, in principle, makes it possible to achieve high yields, but requires management of intermittency and large sun collection surfaces when one seeks to produce large quantities. Defining a process that has acceptable performance and that suits the current and future environmental and societal considerations, requires further study.

It is proposed here to focus on an emblematic and central process of our modern society: metallurgy. The reduction of iron oxide to metallic iron (and steel) by coke is the process that gave rise to the industrial revolution, and has hardly changed in 300 years. The reasons are the following: acting as a fuel, a reducer, and a source of carbon, coke heats the reactor, reduces the iron oxide and to convert iron into cast iron, the latter becoming liquid (this helps recovering it from the blast furnace). This process can be implemented on a very large scale without major problems thanks to the high energy density embedded in coke. This industrial success story is based on the use of cheap coal despite the considerable environmental and societal impacts its use generates. There is currently no carbon-free alternative to cast iron production.

Objectives

A first objective of this phD is to experimentally evaluate four possible metallurgical pathways, each based on a reducing agent either carbon-free or bio-sourced: hydrogen (H_2), ammonia (NH_3), methane (CH_4) and urea (CH_4N_2O). These molecules have different specificities when considering for example their production, transport and storage. The first objective of this research work is to study the actual reduction of pure iron oxide Fe_2O_3 (by-products, reaction conditions, kinetic and yield as a function of the reducing agent), but also of iron oxide ore (so this requires to deal with the slag formation). The second objective will be the development of a solar reactor demonstrator suitable for the continuous production of iron from iron oxide ore, and whose external thermal energy will be entirely provided by solar energy. The final objective will be to evaluate the various metallurgy paths considered in a global manner (including the production of reagents, their possible storage, the reactor, etc ...) taking into account their environmental and societal impacts. For this, the material-energy balance as well as the life-cycle analysis of the various paths will be carried out. For example, all the laboratories involved in this project have driven research on reducing agents production: solar hydrogen production (PROMES), methane production by magnetic catalysis and methanation (LPCNO / LISBP), and production of urea and ammonia by source urine recovery (LISBP). Possibly, other methods to produce these reagents and not specifically studied by these laboratories will be incorporated into this assessment (electrolysis, ammonia synthesis, ...), in order to obtain a relevant evaluation. During this analysis, particular attention will be paid to the global consequences that a modification of the actual metallurgical process could have: extraction channels, supply, and environmental impact. These studies will make it possible to determine the size of the production units and their mesh according to the territories.

The ultimate objective of this thesis will be to propose the most favorable approach for a metallurgical process generating low environmental impacts, optimizing the use of solar energy, and having a positive societal impact.

Skills of the different laboratories and workplan.

This phD will be a collaboration between three laboratories: LPCNO (supervisor: Sébastien Lachaize, co-supervisor: Julian Carrey), PROMES (Stéphane Abanades), and LISBP (Ligia Barna).

PROMES has an expertise in thermo-chemistry, design of solar reactors and hydrogen generation from solar energy. It has all the facilities required to perform solar metallurgical experiments in real conditions (experiments will be carried out at the solar furnace of Odeillo, one of the largest in the world). The LPCNO will bring its expertise in the fields of iron chemistry, structural characterization of materials, and magnetic catalysis. The laboratory is equipped with a solar furnace to study all the processes in laboratory conditions. LISBP will bring its expertise in life cycle analysis, anaerobic digestion, and bio-sourced ammonia and urea production processes.

The first step of this phD will consist in studying the different reactions in the solar furnace (LPCNO) and to design a suitable continuous flow reactor (PROMES). In a second time, the reactions appearing the most interesting will be studied in real conditions, first in batch, then in continuous production (PROMES). Finally, the processes that appear most relevant to this study will be evaluated by life cycle analysis, including the production method of the reducing agents (PROMES / LPCNO / LISBP).

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