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Concentrated solar energy applications in materials science and metallurgy

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ABSTRACT

New energy sources have been researched with the objective of achieving a reduction in the emissions of greenhouse gases as well as other polluting gases. Solar energy is one of the options as when properly concentrated offers a great potential in high temperature applications. This paper offers a review on all fields connected with materials where concentrated solar energy has been applied. These applications include metallurgy, materials processing (welding and cladding; surface treatments; coatings and surface hardening; and, powder metallurgy), and non-metallic materials (ceramics, fullerenes, carbon nanotubes, and production of lime).

1. Introduction

Energy consumption is one of the progress and welfare of societies measurements, and for that reason when there are problems with the energy sources (exhaust, wars, market changes, etc.), then there is an energy problem or energy crisis (for instance, oil crisis in 1973 and 1979, Venn, 2002). In this way, the search for new energy sources and the efficient use of the energy are in the research policies of the countries, especially of the developed countries. These policies form part of the idea of green economy that is rooted in the new industrial policies, with the objective of giving a quality brand to the industries of the developed countries, but also with the purpose of protecting nature and safeguard the health and quality of life of people that live in these countries.

Renewable energies include natural energy sources virtually inexhaustible, either because of being available in huge quantities or being able of regenerating by natural processes. According to this definition, renewable energy includes: biofuels, biomass, geothermal, hydropower, solar energy, tidal power, wave power and wind power. Solar energy is one of the most promising renewable energies as the temperatures that are possible to reach when solar energy is properly concentrated allows melting even ceramic materials, and in this way the number of applications in materials science and metallurgy are almost infinite. However, nowadays, the interest of solar energy is mainly focused on the field of energy, both thermal and electric, except for several research projects where the possible applications of solar energy in materials science are explored. The problem observed in most of these researches connected with materials science is the lack of continuity (not in all of them but is the general keynote), meaning that a certain field is explored and then abandoned, without an attempt of scaling up to pilot plant or industrial scale (searching for a commercial application). The reason for abandoning the topic maybe is the lack of interest by the industrial companies (generally solar processes are competitive in quality, time and temperatures with traditional methods in a laboratory scale but they are not industrially proved, and apart from that, these traditional methods are well known and currently installed in competitive plants) or the lack of promising results (but this question was not observed, in general). In fact, only few projects were scaled from laboratory to pilot scale, and none of them is commercially used in an industrial scale. Moreover, other factors that could limit the possible applications of solar energy in materials science and metallurgy are the uncertainty of sun availability (there are several places that offer an average yearly number of sun hours and sun radiation levels, but they cannot ensure daily weather conditions) or the location of the sun better conditions far from the industrial and populated regions. All above mentioned (and other questions that will be mentioned throughout the paper) could limit the possible applications of concentrated solar energy to materials recently discovered (as could be the case of fullerenes or carbon nanotubes), high added value processes and materials (that could compete with conventional methods) or fields

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Table 1
Parameters defining the operation of each technology (laser, plasma, and concentrated solar energy) (Flamant et al., 1999).

Technology	Typical power (kW)	Flux density (W/cm^2)	Surface area (cm^2)	Temperature (K)	Overall efficiency (%)	Capital cost (kECU/kW)
Laser					≃2	50–100 (1–5 kW)
CO_2	2–5	10^3 to 10^6	< 1	> 5000		
Nd-YAG	≃0.5	10^5 to 10^9 (pulsed)	< 1	> 5000		
Plasma	10–2000	10^4	≃100	> 5000	25	0.8–1.5 (50–1000 kW)
Solar Furnace	≤1000	10^3	≃1000	≤3500	60	1.2–1.8 (50–1000 kW)

where new high energy technologies such as laser or plasma are applied. In Table 1, it is possible to find the parameters that define each technology (laser, plasma, and concentrated solar energy) according to Flamant et al. (1999).

According to Flamant et al. (1999) capital costs and efficiency could be competitive for concentrated solar energy if compared with laser and plasma technologies. However, the couple concentrated solar energy-materials is still an immature technology being this question responsible of the appearance of many different applications in different fields. In order to have a wide view of the possibilities of concentrated solar energy, we will try to collect most of those connected with materials science, metallurgy, and ceramics. As we will see, the couple metallurgy-energy for the ZnO/Zn seems to be the most developed and interesting technology, as this field is the most prolific regarding the number of research projects, but also regarding the scaling up to pilot plant.

First of all, we will try to find the origins of the solar energy application in the field of materials science. It should be considered that modern solar furnaces and solar installations were most of them built in the late seventies or early eighties in a context of energy crisis (1973 and 1979 oil crisis). It should be also considered that solar furnaces and solar installations were originally built with the purpose of searching for new energy sources in a context of high oil prices. There were several previous solar installations, being the most important that proposed by Felix Trombe and built after the Second World War in France. Felix Trombe, Marc Foex and Charlotte Henry La Blanchetais restarted the researches of Lavoisier in the 1946–1949 in Meudon (France) by building a parabolic concentrator of 2 kW used in chemistry and metallurgy at high temperatures, and after that, the 50 kW solar furnace of Mont Sant Louis was built in 1949. However, most of the solar installations were built after the first energy crisis: *PSA, Plataforma Solar de Almería* (early 80 s, 60 kW solar furnace and 3360–7000 kW solar tower, Herranz and Rodríguez, 2010), research is mainly connected with energy issues in this installation; CENIM-CSIC and UCLM (from 90 s, 0.6 kW Fresnel lens equipment, Herranz and Rodríguez, 2010); *PROMES (Procédés, Materiaux et Énergie Solaire, CNRS)* is the main research center that explores the couple concentrated solar energy-materials, which has its early origins in Mont Louis, but being the solar furnaces of Odeillo (final 60 s, different furnaces 0.9 kW, 1.5 kW, 6 kW and 1000 kW (see Fig. 1 and Fig. 2), Herranz and Rodríguez, 2010) the current installation; *Solar furnace of Uzbekistan* (built in 1981, 1000 kW); *High flux solar furnace at DLR (German Aerospace Center)* in Cologne-Porz (1994, power up to 22 kW, Herranz and Rodríguez, 2010), significant experience on testing materials; *Solar Technology Laboratory* at the *Paul Scherrer Institute (PSI)*, stablished in 1988 in Villigen (Switzerland), they offer the High-Flux Solar Furnace (1997, 40 kW), 300 kW solar pilot plant (commissioned in 2005, EU project SOLZINC) to perform the carbothermal reduction of zinc oxide, and 100 kW solar pilot plant (commissioned in 2011, BFE project Solar2Zinc) for the thermal dissociation of zinc oxide to produce zinc and syngas; *Weizmann Institute of Science* of Israel (3000 kW solar tower, from the late 80 s; 50 kW solar furnace from the early 80 s); *National Solar Thermal Test Facility (NSTTF)* operated by Sandia National Laboratories for the U. S. Department of Energy (1979, 16 kW solar furnace, Herranz and Rodríguez, 2010); *National Renewable Energy Laboratory (NREL)* (1977), have a high-flux solar furnace of 10 kW in operation since 1990 in Golden (Colorado); *Korea Institute of Energy Research (KIER)*, (21st century, 40 kW solar furnace; 10 kW disc type solar concentrator), mainly dedicated to solar applications in the field of energy (Konstandopoulos et al., 2012); and, *Commonwealth Scientific and Industrial Research Organization (CSIRO)*, (21st century, 500 kW solar tower) also mainly devoted to solar applications in the energy field (Konstandopoulos et al., 2012).

Fig. 1. Medium size solar furnace at Odeillo (1.5 kW foreground, 0.9 kW background).

Fig. 2. 1000 kW solar furnace of Odeillo.

Historically, the first use of concentrated solar energy in the transformation of materials is found in the Roman's period. During the Siege of Syracuse (Second Punic War, 215 before JC) the legend tells that Archimedes used mirrors to destroy the Roman naval fleet composed of wooden ships (Rossi 2010). However, the first real and most important application of solar energy in materials processing is the sun drying of adobe bricks, low temperature sun process applied since at least 10,000 years (Revuelta-Acosta et al., 2010; Rodríguez and Soroza, 2006). In this line, Martínez et al. (2015) studied the applications of