



Temperature uniformity improvement in a solar furnace by indirect heating



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ABSTRACT

The development of materials capable to work under increasingly extreme conditions requires not only higher processing temperatures but also tight control of temperature uniformity. Aiming at developing an indirect heating receiver design to be integrated in novel concentrated solar furnace for the thermal processing of materials under controlled heating and homogeneous temperature, graphite disc heat receiver systems with varying thickness, geometry and height from the sample holder at the bottom were tested in two types of gas environments, namely dynamic vacuum and under Ar gas flow. Results acquired were quite encouraging demonstrating feasibility of realizing temperature gradient within circa 50 °C along the height beneath the top graphite disc and the bottom sample holder.

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1. Introduction

The interest of using highly concentrated solar power (CSP) for processing of materials is not new. Indeed, at the beginning of the XXth century, the Portuguese catholic priest Manuel António Gomes created and patented an apparatus for making industrial use of solar heat for attaining high temperatures required in metallurgical and chemical researches (Himalaya, 1901, 1905). He was a very tall man, and for this reason was nicknamed “Father Himalaya”. He called this device – Pyreliophorus – which made use of a concentric parabolic array of mirrors to concentrate the sunlight, instead of a lens, where temperatures as high as 3500 °C could be reached, enough to melt many different types of materials using solar energy, including metals and rocks. Father Himalaya was a pioneer in Portugal of the solar energy and other renewable energy usage. Modern solar furnaces are inspired by his pioneering work.

Still nowadays very little use is made of solar furnaces for processing of materials. Not only such facilities require high capital investment and are expensive to operate and maintain, but also it is rather difficult to control temperature in such a way that the process can be technically feasible in large-scale commercial plants (Herranz and Rodríguez, 2010; Martínez Plaza et al., 2015).

When materials are directly exposed to concentrated solar radiation, it is rather difficult to ensure a homogenous temperature distribution over the material being exposed, due to Gaussian distribution of the energy density in the focal area (Martínez Plaza, 2013). One way to tackle such drawback is to make use of secondary concentrators (Steinfeld and Schubnell, 1993). However, data on their ability towards achieving temperature uniformity for the scaling of solar reactor from the laboratory (e.g. 2 kW) to the industrial scale (some hundreds of kW) for reliable solar material processing at the industrial size is still unavailable. Additionally, another key issue preventing wider usage of solar furnaces concerns the measurement of the thermal radiation emitted by solar irradiated material surfaces in a simple and reliable manner. Although several methods have been developed there is not yet a consensual solution on how such measurements should be carried out. Basically, three methods have been developed for decoupling the emitted and reflected components of the radiosity: flash-assisted multi-wavelength pyrometry (FAMP) (Schubnell et al., 1996), pyroreflectometry (Hernandez et al., 1995), and solar-blind pyrometry (Crane, 2010). An advantage of FAMP and pyroreflectometry is that, the emissivity of the surface is measured *in situ*. However, they both require continuous sampling of the radiation from a cold reference target of known reflectance at various wavelengths.

In solar furnaces where the samples are irradiated with highly concentrated solar radiation, the emitted radiation is mainly due

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to reflected solar radiation from the irradiated sample. Thence, pyrometric temperature measurement of solar irradiated material surfaces is regarded as a good alternative to contact measurement even though the determination of the real temperature requires knowledge of the surface emittance. Although, the reflected radiation and the use of glass windows for material testing in vacuum or controlled atmosphere can be important sources of error, it has been shown that use of the so-called “solar blind” pyrometer with a band-pass filter centred at around 1400 nm works well at temperatures over 1100 K even through quartz windows (Ballestrín et al., 2010; Marzo et al., 2014).

It is possible to measure surface temperature more accurately using two single colour pyrometers operating at different wavelengths (1.54 and 5.21 μm) allowing emissivity determination (Crane, 2010). However, only surface rather than bulk material temperatures can be determined by this method. Indeed, in previous works, we have demonstrated that growth of nanometer size WC whisker at the top surface directly exposed to the concentrated solar beam was attributed to a surface singularity (Dias et al., 2007; Oliveira et al., 2008). Besides, the use of colour filters to cut some sunlight radiation wavelengths was found particularly useful to produce N-rich carbonitrides under direct exposure conditions in N_2 atmospheres (Oliveira et al., 2012). We have also shown that sintering of cordierite ceramics could be achieved by indirect heating with solar radiation (Oliveira et al., 2009) but not by direct exposure to concentrated solar beam (Oliveira et al., 2005). Bearing this in mind, it seems that solar processing of materials under controlled and reliable heating conditions might be achieved in an indirect manner. This requires selection of suitable materials that can be used as heat absorbers capable to transfer heat at high temperature in an efficient and cost-effective way. Unfortunately, the range of available materials is rather limited. In the 2014 test campaign carried out at PSA, we tested this concept using two receiver materials (stainless steel AISI 310 and MoSi_2) and three configurations were studied (Li et al., 2015). A thermal model was also developed and validated by the experimental data obtained. However, tests had to be carried out in static air up to 800 °C. To raise operating temperatures, graphite would be an interesting option owing to its resistance to high temperature as well as its good thermal conductivity and well known high surface emissivity. For that end, we have developed a sealing quartz window system enabling us to operate under vacuum (around 2×10^{-1} mbar) or any oxygen-free environment at temperatures up to 1600 °C. Some recent results obtained at PSA in the 2015 test campaign in this domain are presented and discussed in this paper.

2. Experimental

2.1. Test setup

In the 2015 test campaign, the new PSA high concentration solar furnace SF40 (Rodríguez et al., 2016) was used. Briefly, it is a 40 kW power furnace reaching a peak concentration exceeding 7000 kW m^{-2} (7000 suns) in a focus of 12 cm in diameter. It basically consists of a 100 m^2 flat heliostat, a parabolic concentrator with a projecting area of 56.5 m^2 , slats shutter, and test table with three axis movement (Fig. 1). The heliostat tracks the sun and reflects the collimated sunrays horizontal and parallel to the optical axis of the parabolic concentrator (8.5 m in diameter), which in turn concentrates the incoming rays into the focus of the parabola (at circa 4.5 m). The louvered shutter regulates the amount of sunlight incident on the concentrator and therefore the radiant energy into focus by the angular motion of its slats. The SF40 Test Table platform consists of a square plate of 550 mm side, which is run by three SKF linear actuators with transmission by spindle,

which transmit motion in three spatial dimensions, east-west (X axis: 1000 mm), north-south (Y axis: 700 mm) and up-down (Z axis: 615 mm), allowing the table to be placed anywhere in the focal zone, so that tests can be carried out under precise control conditions (± 1 mm). This is a major requirement since processing of materials involves generally a tight control of temperature uniformity. The problem becomes especially acute when scaling-up to larger commercially viable part sizes.

Some tests in solar furnaces are carried out under vacuum or controlled atmosphere conditions, in order to avoid oxidation of the samples at high temperatures by the action of atmospheric oxygen (Kruesi et al., 2011; Oliveira et al., 2016). On the other hand, the reaction chamber for materials processing requires typically very high working temperatures in the range of 1200–2000 °C, and thence graphite was selected as the receiver material in view of its resistance to high temperature (up to 2600 °C) as well as its good thermal conductivity ($65 \text{ W m}^{-1} \text{ K}^{-1}$) (Schunk, 2009) and known emissivity (ranging from 0.7 to 0.9, depending on the temperature) (Mikron, 2016; Kostanovskii et al., 2005). However, graphite must be used in oxygen-free environments; and therefore it is normally used in furnaces where the atmosphere is inert (e.g. vacuum or inert gas). To this end, a new reaction chamber window had to be designed and manufactured (Fig. 2, top). It consists of a quartz glass with 250 mm in diameter and 20 mm in thickness placed on a water-cooled flange which greatly improves the seal compared to previously existing chambers and prevents its overheating. Sealing is accomplished using two Viton® O-rings, one in direct contact with the glass and the other with the top sealing steel surface of the reaction chamber so-called “Minivac” (Fig. 2, bottom). By doing so, it was possible to carry out high-temperature solar-irradiation tests using graphite plates in vacuum (2.4×10^{-1} mbar) and in argon (60 L h^{-1}), without any evidence of oxidation of the graphite.

Moreover, since these tests were performed in vacuum and controlled atmosphere, on the horizontal plane, it was necessary to use a tilted mirror at 45° so that it reflects the concentrated focal beam by exactly 90° and projected it onto the horizontal plane.

Thirty-five (35) tests were carried out during the 10-working day 2015 test campaign. The test conditions used are summarized in Table 1.

2.2. Temperature measurements setup

Test runs E1 up to E4 were carried out to obtain calibration curves for temperature measurement, comparing the temperature readings given by an optical pyrometer and a B-type thermocouple. To avoid undesirable reaction between the Pt-based thermocouple and the graphite, particularly under vacuum, the thermocouple had to be shielded using a closed alumina sheath. For temperature calibration tests, 10 mm thick graphite disc of 80 mm in diameter was placed on the top of an alumina fibre plate according to the setup shown in Fig. 3. Upon exposure to the radiation beam, data obtained during the first three test runs had to be ruled out owing to a reaction which took place leading to the formation of a dark deposit on the underneath quartz surface window and a change in colour of the graphite plate, particularly evident at temperature above 1400 °C (not shown). Such dark deposits are attributed to condensation of carbon-rich vapour species originated mainly from the irradiated graphite plate which was not ever used before. Both events are expected to have affected optical pyrometer measurements which were carried out in the vicinity of the B-thermocouple location. Thence, a valid calibration curve could only be obtained for test run E4, which was carried out under argon flowing at 60 L h^{-1} introduced at the top part of the Minivac furnace, thus avoiding condensation of undesired species. For obtaining the calibration curves, the shutter was opened by

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