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Solar tower based aluminum heat treatment system: Part I. Design and evaluation of an open volumetric air receiver

P. Sharma [a], R. Sarma [b], L. Chandra [b,*], R. Shekhar [a], P.S. Ghoshdastidar [a]

[a] *Indian Institute of Technology, Kanpur 208016, India*
[b] *Indian Institute of Technology, Jodhpur 342011, India*

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Abstract

Electrical energy is employed for processing operations of material, such as, smelting, soaking and heat treatment. During this process, fossil, coal, and nuclear as a fuel is employed. Extraction and use of these fuel sources have serious environmental implications. Moreover, the employed process involves conversion of fuel to heat and then to electricity. Double conversion process can be avoided by directly introducing hot air provided by a solar tower equipped with a volumetric air receiver into a retrofitted furnace. This is a clean, green alternative for generating high temperatures required for metals processing operations. Initially a system would be developed for the heat treatment of aluminum, which requires temperature between 290 and 400 °C. A survey of the literature shows that quantitative design basis of individual volumetric air receiver components is conspicuous by its absence. Hence the objective of this investigation has been to use principles of fluid flow and heat transfer to design individual components of an Open Volumetric Air Receiver (OVAR) system. Experiments on a 2 kW_{th} Solar Air Tower Simulator system (SATS) validate the process used in designing individual components of the OVAR. The ultimate aim of this research is to develop a system that can be used for heat treatment of steels and other possible extractive metallurgy operations such as the smelting of metals from its ores.

Keywords: Concentrated solar thermal; Open volumetric air receiver; Solar air tower simulator; CFD and experiment

1. Introduction

Fossil fuels, either directly or indirectly as electricity, are extensively used in metals processing operations such as melting, soaking and heat treatment. Extraction and use of these fuel sources have serious environmental implications, issues pertaining to which are well known. One clean, green method of operating metal processing furnaces is by the use of CSP tower technology. Temperatures ranging from 450 °C to upwards of 750 °C are necessary for heat treating a variety of metals such as aluminum, copper and steel. Metals such as aluminum and its alloys can also be melted in the above-mentioned temperature range, while copper and steel need temperatures in excess of 1000 °C. Direct, concentrated solar irradiation of rotary kilns through an aperture for aluminum scrap remelting has been proposed. However, the kiln would require expensive retrofitting to change the existing refractory lining to withstand the intense solar radiation and erosion due to aluminum scrap (Funken et al., 2001). Efforts to produce Al/Si alloy through a 70 kW tracking parabolic concentrator are made (Murray, 2001). For metals processing operations, a method that can use concentrated solar radiation with minimum retrofitting of existing commercial reactors/processes is required.

* Corresponding author.
E-mail address: chandra@iitj.ac.in (L. Chandra).

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Versatility is the major advantage of CSP; it can be used to simultaneously generate electricity and high temperature process heat in varying proportions, depending on the need. This strategy would fit perfectly in aluminum plants, which require electricity for smelting and heat for soaking and heat treatment. Providing solar electricity to smelters is straightforward. However, a methodology for the use of CSP for heat treatment is necessary. One possible method is to use air as a thermic fluid in solar towers that allows achieving the desired high temperature. A schematic diagram of the proposed system is shown in Fig. 1a. Here, a solar tower equipped with a volumetric air receiver provides hot air to a retrofitted furnace for maintaining the required high temperatures for metals processing operations. Fig. 1b shows an industrial aluminum heat treating furnace, where electrically heated air is used to attain the requisite temperatures by forced convection heating. Capacity of this furnace is about 1 MWe. Clearly, integrating these furnaces with CSP would not require major modifications. Consequently, the major objective at the Indian Institute of Technology Jodhpur (IITJ) was to design and set-up a 100 kW_{th} integrated volumetric air receiver-convective furnace system, with thermal storage. Since the design of the furnace was available from one of India's foremost aluminum companies, the initial task was to design a volumetric air receiver assembly. Because of their inherent advantages over a closed air receivers (Avila-Marin, 2011), an open volumetric air receiver configuration was preferred.

Solar tower technology with volumetric air receivers has attracted a lot of attention because air, despite its disadvantage of relatively inferior thermal properties, can be heated to higher temperatures and is a simpler thermic fluid to work with compared to molten salt. The heart of a volumetric receiver is a porous body, referred to as the absorber with a specific porosity so that the concentrated solar radiation that is reflected by a field of heliostats is absorbed in the depth of the structure. The concentrated solar radiation, which is focused on one end of the receiver, heats the absorber. Air is sucked into this absorber and heated volumetrically in the pores.

Most investigations on receivers have focused on different aspects of absorbers such as choice of materials as function of absorber outlet temperatures (metals, SiSiC, SiC), porous structures (foam, honeycomb, wire mesh), heat transfer to the thermic fluid, and flow instability (Fend et al., 2004; Avila-Marin, 2011; Wu and Wang, 2013). A number of studies have focused on the macroscopic characterization of different types of receivers such as the maximum absorber outlet temperature and thermal efficiency as a function of the ratio of power on aperture and air mass flow rate (Avila-Marin, 2011).

Agrafiotis et al. (2007) have stated that the non-uniform temperature distribution across the receiver cross-section can adversely affect the mechanical properties of the receiver components, most notably the absorbers. Hence there is a need to cool the absorbers to mitigate thermal stresses. The importance of cooling the absorbers was also demonstrated in the SIREC receiver (Avila-Marin, 2011), but details of the absorber cooling system, to the best of our knowledge, is not available in the literature. The need to increase the air return ratio (ARR) has been emphasized (Marcos et al., 2004), although the number of studies are limited (Ho and Iverson, 2014). The influence of different volumetric receiver designs, such as, external, semi-cavity, cavity and cavity with secondary concentrator geometries (billboard or cylindrical absorber) and different air return modes (centralised, distributed through multi-channels, etc.) have been analyzed (Marcos et al., 2004).

Flow instability has been pointed as one major problem, which could result in the failure of absorbers in volumetric air receivers (Avila-Marin, 2011; Pitz-Paal et al., 1997). The non-uniform solar radiation incident on the absorber surface, above a critical heat flux, may result in local overheating and thereby increase in viscosity (Becker et al., 2006). This will lead to localized reduction in the mass flow rate of air in the affected pores, which, in turn, will lead to a further increase in local temperatures, ultimately resulting in the failure of the absorber. The effect of material property of absorber such as thermal conductivity on flow instability has been demonstrated in (Becket et al., 2006, Sharma et al., in press); it was observed that absorber material with low thermal conductivity may lead to flow instability.

The development of volumetric air receiver has been reported since the early eighties (Hoffschmidt et al., 2003). The open loop volumetric receiver technology with metallic receiver has been demonstrated in Mk-1, Sulzer, Catrec, TSA, Bechtel, SIREC (Avila-Marin, 2011;

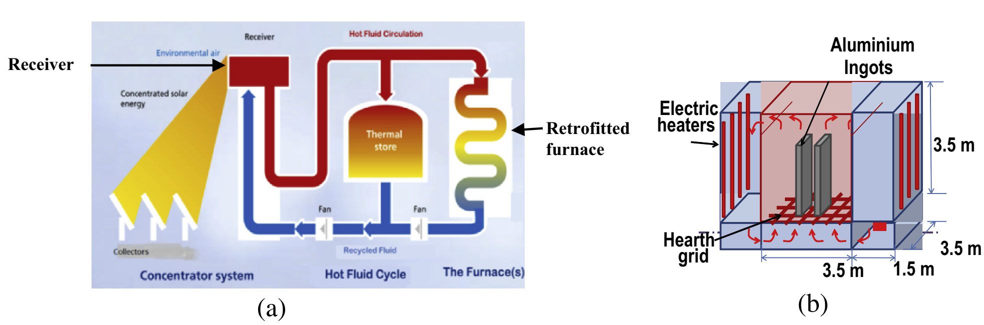

Fig. 1. Schematic of the proposed volumetric air receiver based solar convective furnace system and (b) electrically heated industrial aluminium heat treatment furnace.