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Thermal and hydrodynamic behavior of ceramic volumetric absorbers for central receiver solar power plants: A review

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ABSTRACT

This paper presents an extensive review of the thermal and hydrodynamic behavior of conventional ceramic volumetric absorbers, i.e. monolithic honeycombs and open-cell foams. It is intended to provide scientific support to the design of more efficient absorbers with novel structures and materials, based on a further understanding of how the characteristics of conventional absorbers modify their performance. This review identifies radiative and thermal properties that a good absorber must have, providing reference values for SiC absorbers. An overview on how the typical manufacturing process modifies their properties is also presented. Significance of geometrical parameters and radiative and thermal properties of both type of absorbers, as well as the effects of incoming light direction on the solar radiation propagation and the solid-air temperature distributions within their structure are discussed. Typical operating conditions of these elements are given. Their characteristic outlet air temperature and thermal efficiency are compared and discussed. The different mechanisms that are responsible for the pressure drop in these elements are identified, and their influence on the heat transfer mechanisms is analyzed. To conclude, factors that promote the appearance of flow instabilities are described.

Contents

Abbreviations: HTF, Heat transfer fluid; LCOE, Levelized cost of electricity; MC, Monte Carlo; MH, Monolithic honeycomb; OCF, Open-cell foam; reSiC, Recrystallized silicon carbide; SiC, Silicon carbide; SiSiC, Silicon carbide infiltrated with silicon

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1. Introduction

One of the main challenges of solar thermal electricity is the reduction of its levelized cost of electricity (LCOE) to improve its competitiveness with respect to other electricity generation methods. One route to achieve this goal consists of increasing the solar-to-electricity energy conversion efficiency by reducing losses in the conversion chain from the heliostat field to the power block and/or by using higher inlet temperatures in the power cycle. In this context, volumetric receiver technologies aim to minimize the radiative heat losses from the receiver aperture while allowing for higher operating temperatures. However, the performance obtained so far with the structures that have been used as volumetric absorbers are modest. In order to increase the competitiveness of this technology in the electricity market of tomorrow, it is essential to develop a new generation of optimized absorbers with novel structures and materials. This review aims to show how the different features of conventional ceramic absorbers influence their behavior, in order to provide a scientific basis for the design of more efficient configurations.

Volumetric receivers mainly consist of a permeable porous absorber that enables the propagation of incoming concentrated solar radiation within its structure. The absorbed energy is transferred by convection to a heat transfer fluid (HTF) that flows through it, either at atmospheric or pressurized conditions. Typically, air is used as HTF since it is freely available and it is non-toxic; however, gases such as carbon dioxide could also be employed because of its higher heat capacity at high temperatures. Ideally, maximum absorber temperatures should be achieved inside the absorber material (this is the so-called volumetric effect), so that the temperature on the irradiated surface of the volumetric receiver is lower than would be in tubular absorbers, thus leading to smaller radiation losses. The principles of operation of both types of receivers are illustrated in Fig. 1.

Different aspects of the thermal characteristics of volumetric absorbers have been analyzed in the literature, such as the propagation of the incident radiation within the absorber [2–12]; the temperature distributions of solid and HTF, calculated in numerical simulations of the coupled conductive–convective–radiative heat transfer mechanisms occurring in this element [4–6,10–14]; or the maximum achievable air outlet temperatures and thermal efficiencies that have been measured in experimental campaigns [1,13,15–17].

As maximizing overall efficiencies requires minimizing parasitic energy consumption, suitable absorber architectures must be designed so as to maintain the receiver pressure drop within reasonable limits. Several authors [18–21] have studied the hydraulic behavior in different volumetric absorbers to identify the mechanisms that are responsible for the pressure drop in these elements, which significantly affects the convective heat transfer process within them too. During the operation of volumetric absorbers, undesirable flow instabilities may also appear, which reduce their thermal efficiency and may cause structural damages. Consequently, there have been theoretical and experimental analysis [13,16,22,23] which focused on determining the causes and conditions that originate and promote this phenomenon.

In this paper, Section 2 describes monolith honeycombs and open cell foams, which are the main structures generally used as volumetric absorbers; and which this manuscript focuses on. Section 3 details the radiative and thermal properties required in high efficiency absorbers, gives reference values for SiC absorbers and discusses the effects of manufacturing processes. Section 4 addresses the concentrated solar radiation propagation within absorber structures, and its dependence on material properties, geometrical design parameters and incoming light directions. Section 5 describes the heat transfer mechanisms and thermal performance, including a description of typical operating conditions in volumetric receivers. Finally, Section 6 focuses on the hydrodynamic behavior of absorbers, in relation to their thermal performance too.

2. Conventional structures

In the last three decades, the main studies on volumetric absorbers have been focused on commercial porous structures such as high temperature filters and catalyst carriers, which were tested as absorber elements under solar conditions, i.e. high heat fluxes and temperatures in oxidizing atmospheres.

Metallic materials such as the Inconel 601 have good oxidation resistance at high temperature. For this reason, it was selected to manufacture the knitted wire meshes employed in the solar receiver of the Phoebus-TSA (Technology Program Solar Air Receiver) project, where a maximum air temperature of 950 °C [24] was achieved. For higher temperatures, however, ceramic materials are the best alternative because of their higher melting point. Monolithic honeycombs (MH) and open-cell foams (OCF) are the main ceramic structures that have been used as volumetric absorbers to date.

MH absorbers are based on tessellating patterns that produce parallel channels in the direction of the fluid flow. Most studies concerning MH absorbers have employed structures with square cross section channels, being the absorber modules of the SOLAIR (Advanced Solar Volumetric Air Receiver for Commercial Solar Tower Power Plants) project some of the most representative of its kind (Fig. 2).

OCF absorbers are composed of a huge number of randomly packed open cells with different sizes and shapes, which form a highly porous foam-like structure as shown in Fig. 3. The

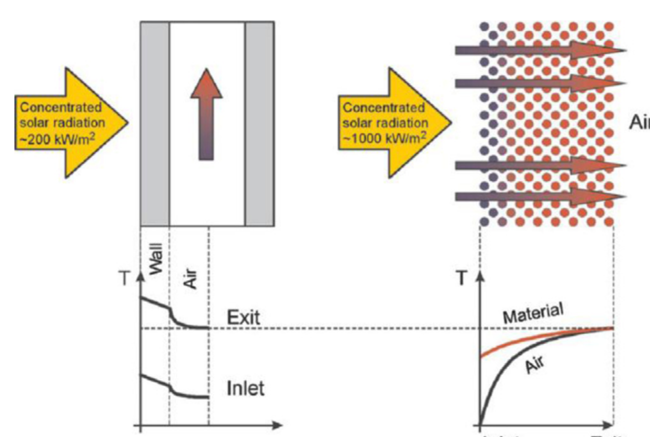

Fig. 1. Principle of operation of a tube receiver (left) and a volumetric receiver (right) (from [1]).