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Determination of critical thermal loads in ceramic high concentration solar receivers

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A B S T R A C T

Solar towers with volumetric air receiver technology are a promising technology for continuous or demand oriented electricity supply from a sustainable resource with competitive costs. The absorber elements used for this receiver technology are permeable ceramic honeycombs, which are heated up by concentrated solar radiation. Afterwards the heat is being transferred to air, which finally feeds the steam generator of a Rankine-Cycle. Resulting from the intensive solar flux of up to 800 kW/m^2, the absorber modules are exposed to severe thermal loads. Maximum temperatures of more than 1000 °C are reached. Furthermore, during daily start-up and shut down procedures and additionally during cloud transitions the absorbers undergo transient heat loads, which might reduce their lifetime. The objective of the present study is to quantify the effect of typical thermal loads and to calculate the resulting mechanical stresses inside the absorber modules. Two types of absorbers have been compared, a conventional coarse honeycomb and an advanced one with a higher cellularity offering an improved efficiency potential. The mechanical strength of the cellular material is used to find out whether the computed thermomechanical stresses are critical or not. Finally, experimental thermo-shock tests have been carried out to validate the numerical models. It could be shown that under normal operation the thermo-mechanical stresses remain in a range markedly below the fracture stress in both absorber variants. As a consequence, limits are given to what extent the material should be thermally loaded during operation.

1. Introduction

Some time ago, in the late 90ies of the last century, ceramics was assigned a promising future, because of its wide spectrum of use and its superior properties [1]. However, besides excellent strength and elasticity properties at high temperatures, ceramic materials show drawbacks concerning resistance to temporal and spatial thermal gradients. To overcome these problems a thorough prediction of the stresses due to thermal loads is necessary.

The study reported deals with the characterization of the thermo-mechanical properties of a siliconized silicon carbide (SiSiC) honeycomb structure, which is used as an open volumetric receiver for a solar tower. Thanks to its high application temperature of more than 1300 °C SiSiC is the material of choice for high temperature applications in solar energy. However, since SiSiC – like monolithic ceramics in general – is not able to undergo plastic deformations, it is very sensible to thermo-shock loads. Thus, the main aim of the study is to find out determined limits for stationary and transient thermal loads during application in order to ensure a safe and durable operation of the system.

Numerous studies have been published since the mid 80ies of the last century dealing with SiSiC honeycomb structures applied as open volumetric receivers for concentrated solar radiation in solar tower technology. In this application, a large number of tracked mirrors direct the solar radiation to a central receiver on top a tower. This principle has been also realized and demonstrated in the experimental Solar Tower Jülich (Fig. 1). The receiver of this plant consists of 1080 modular absorbers transferring the absorbed heat to an air flow, which finally feeds the boiler of a steam turbine. The absorber modules used are shown in Fig. 2.

Most of the studies focused on heat transport and solar-to-thermal efficiency [2–4]. A comparative review of these studies is presented in [5]. The honeycomb structure material's thermophysical and heat transfer properties are presented in [6]. A detailed analysis of the volumetric solar absorber along with experimental data of the thermo-mechanical properties before and after long-time thermal operation including pore size distribution, microstructure and influence of the manufacturing process is given by Agrafiotis [7]. Avilar-Marin and Hoffschmidt comprehensively describe the European projects HITREC II

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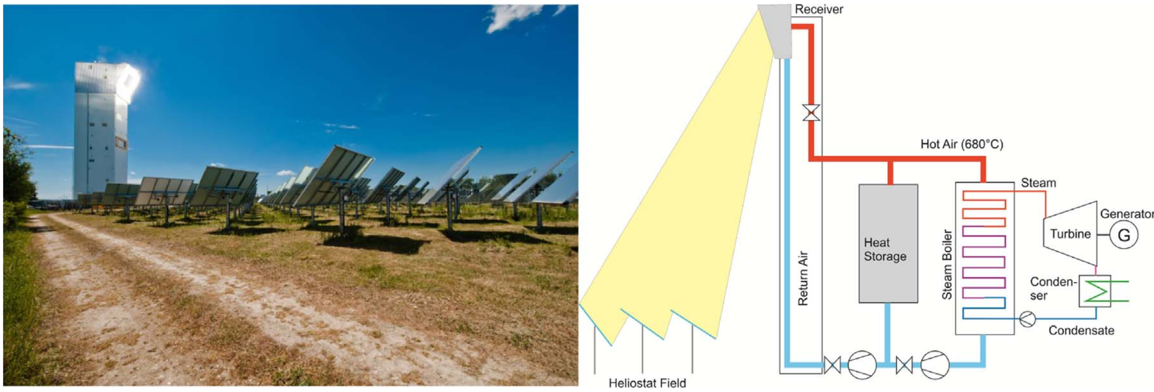

Fig. 1. The Solar Tower Jülich and its working principle.

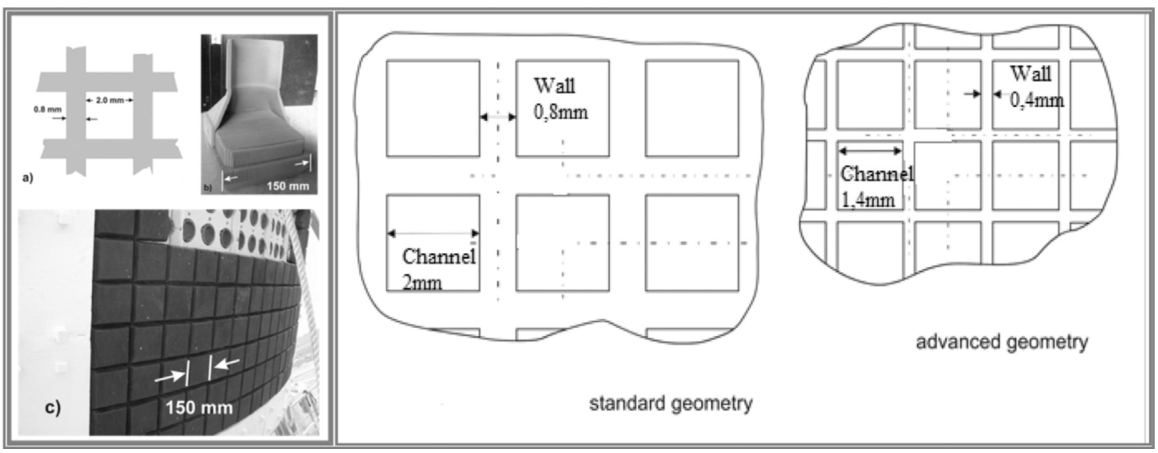

Fig. 2. The modular receiver system of the Solar Tower Jülich (left), cross-sectional view of the absorber with cell density 80 cpsi (standard geometry) and 200 cpsi (advanced geometry).

and SOLAIR under the leadership of the Spanish company Abengoa [8,9]. They have been the basis for the development of the Solar Tower Jülich.

A review on the various technologies to model the fluid-dynamical and heat transfer phenomena of open volumetric receivers has been published by Capuano [10]. A thorough theoretical discussion of the constraints of the open volumetric receiver is given by Kribus [11]. He states that under certain conditions flow instabilities can occur, which may lead to an overheating of the receiver. Wu and co-workers [12] published an extensive study on heat transfer properties of ceramic foams foreseen as open volumetric receiver elements, which enabled them to subsequently present a detailed transient model to fully describe the performance of ceramic foam applied as an open volumetric receiver [13].

Common sense in these studies is the fact, that the general performance of a volumetric receiver is better if the material exhibits the following features: high cellularity (to create large surfaces for solid-to-gaseous heat transfer) and high porosity (to let the concentrated radiation deeply penetrate into the volume of the cellular structure). This has also been confirmed by a detailed parametric study based on a continuum model by Capuano [14]. Furthermore it has been shown that the effective thermal conductivity in the direction perpendicular to the main flow direction directly influences the operation stability of the receiver. This can be achieved either by employing a material of high thermal conductivity (like the SiSiC in case of the HiTRec technology) or by a porous structure, which allows the fluid to move also in directions different from the main flow direction [15].

However, studies on thermal loads and their accompanying mechanical stresses have not yet been presented, although a precise knowledge on this topic could significantly improve the durability, safety and reliability of the receiver during everyday operation. On the one hand the overall operation experience of the solar volumetric absorber in solar tower technology has shown a good reliability of the structure, on the other hand the effect of critical temporal and spatial temperature gradients influencing the structure stability has not yet been investigated.

The current study aims at a thorough investigation of the influence of typical thermal loads occurring during regular operation on the mechanical stresses inside the absorber. Two types of structures have been considered: the standard one (80 cpsi[1])and an advanced one with a finer cell structure (200 cpsi, Fig. 2).

2. Method and experimental set-ups

2.1. General procedure

The general procedure used to carry out the study has been as follows:

– Determination of a typical maximum thermal load during regular operation of an absorber in a Solar Tower
– Development of a coupled flow/heat transport model and calculation of the time-dependent temperature distribution, which corresponds to the thermal load defined in the first step
– Applying an appropriate thermomechanical model to compute the mechanical stresses, which arise as a consequence of the temperature distributions inside the component during operation
– Determination of the mechanical strength of the employed cellular

[1] cpsi: cells per square inch.