Solar Energy 174 (2018) 342–351

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Exploiting volumetric effects in novel additively manufactured open solar receivers

S. Luque[a], G. Menéndez[a,1], M. Roccabruna[b], J. González-Aguilar[a], L. Crema[b], M. Romero[a,*]

[a] IMDEA Energy Institute, Avda. Ramón de la Sagra 3, 28935 Móstoles, Spain
[b] Fondazione Bruno Kessler, Unit of Applied Research on Energy Systems, Via Sommarive 18, 38123 Trento, Italy

ARTICLE INFO

Keywords:
Concentrating solar energy
Central receiver systems
Open volumetric air receivers
Forced convection
Thermal radiation
Performance testing

ABSTRACT

The development of additive manufacturing techniques is allowing for the design of highly customised components with enhanced functionality in many application sectors. This paper describes the full aerothermal assessment of four novel hierarchically-layered fractal-like volumetric absorbers, designed to be employed in high temperature concentrating solar power applications. Absorbers are built by the lateral repetition of elementary cells on a 2D plane, which are arranged into constituent layers and stacked up following fractal growth patterns. They have been manufactured in stainless steel by selective laser melting. By fine tuning both the geometry of elementary cells and their growth patterns, the absorber porosity distribution can be tailored on a per-layer basis. This leads to optimised aft-shifted radiation absorption profiles and allows for the introduction of intricate convective heat transfer augmentation features. Experimental temperature measurements are presented which demonstrate that these variable porosity absorbers are able to generate and exploit volumetric effects, an advancement with respect to both monolithic honeycombs and isotropic foams. Solar-to-thermal conversion efficiencies, however, are shown to be of the same order as in those other receiver geometries. It is argued that the main reasons for this lie in the use of stainless steel, a material of relatively high reflectivity, and the predominantly low convective heat transfer rates found in the laminar flows established in these components.

1. Introduction

Solar receivers able to provide ever higher output temperatures at very high irradiance levels constitute one of the key elements to achieve high thermal conversion efficiencies in concentrating solar power plants. Three major solar receiver concepts can be found to date (Becker and Vant-Hull, 1991): tubular receivers, fluid/particle receivers, and volumetric receivers. All of them transform incident concentrated sunlight into thermal energy at the temperature required by the downstream mechanical, thermal or chemical conversion process. Regardless of the working fluid or thermodynamic cycle employed, design trends towards higher absorber output temperatures are general. Target operating conditions for their widespread industrial deployment are demanding (Mehos et al., 2016): working fluid temperatures at receiver exit in excess of 1000 K, thermal conversion efficiencies over 90%, minimum service life of 10 000 cycles and overall costs below 150 USD per kilowatt of thermal power delivered. Operating temperatures play a conflicting role in their performance because thermal losses become significant at the very high levels required for efficient downstream thermochemical or power cycles.

Volumetric receivers consist of radiative-convective heat exchangers in which porous interlocking structures are arranged to fill a volume. Concentrated solar radiation is gradually absorbed and conducted into their solid volume, and transferred to a working fluid by forced convection. The objective is that maximum receiver operating wall temperatures occur deep inside the heat exchanging matrix to reduce thermal emission losses from the aperture. When this occurs, it is also possible that the temperature of the working fluid leaving the receiver is higher than that found in its irradiated front face. The attainment of both of these conditions is widely referred to as the volumetric effect (Boehmer et al., 1991). The working fluid employed in open volumetric receivers is typically air because of its abundance, low environmental impact, and ability to reach very high temperatures without phase change or thermal degradation. Closed-loop pressurised volumetric receivers also exist, which employ external quartz windows to seal the flow field (Pozivil et al., 2015).

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[*] Corresponding author.

E-mail addresses: salvador.luque@imdea.org (S. Luque), MenendezRodriguezG@cardiff.ac.uk (G. Menéndez), roccabruna@fbk.eu (M. Roccabruna), jose.gonzalez@imdea.org (J. González-Aguilar), crema@fbk.eu (L. Crema), manuel.romero@imdea.org (M. Romero).

[1] Present address: Cardiff School of Engineering, Cardiff University, The Parade, Cardiff CF24 3AA, UK.

https://doi.org/10.1016/j.solener.2018.09.030
Received 4 January 2018; Received in revised form 11 September 2018; Accepted 12 September 2018

Nomenclature

ε	porosity
A_v	cumulative specific surface area, $m^2\,m^{-3}$
$\dot{m}$	mass flow rate, $kg\,s^{-1}$
Q_0	incident power on aperture, W
T	static temperature, K (°C)

Subscripts

air,in	referred to the air inlet plane
air,out	referred to the air outlet plane
front	referred to the absorber front wall
rear	referred to the absorber rear wall
th	thermal

Acronyms

2D, 3D	two-, three-dimensional
AISI	American Iron and Steel Institute
CAD	computer-aided design
IR	infrared
SLM	selective laser melting

High (or selective) solar absorptivity, high (or directional) thermal conductivity, mechanical durability at severe operating conditions, and, where possible, low cost are desired features for volumetric receiver materials – especially if they are to operate under volumetric effect conditions. In addition, the geometry must be designed to allow for effective heat transfer processes, including an adequate absorption of incident radiation as a function of depth, high thermal conduction towards the interior, and high convective heat transfer coefficients. Minimising the pressure drop across the receiver is also desirable. The design of volumetric receivers is thus one of conjugate heat transfer processes and interconnected optical and thermal requirements where trade-offs are unavoidable.

There exists scarce experimental evidence of solar receivers achieving a significant volumetric effect. The exception is a double-layer selective receiver composed of an external silica square-channel monolithic honeycomb and an internal layer of silicon carbide particles (Menigault et al., 1991). A similar double-layer configuration where the internal particle layer was replaced by a ceramic silicon carbide monolith did not show the same behaviour (Pitz-Paal et al., 1992), however. Neither did, to name but a few studies, more conventional single-layer silicon carbide monolithic honeycombs (Téllez, 2003; Hoffschmidt et al., 2003), stainless steel wire grids (Ávila Marín et al., 2014), nor ceramic foams (Fend et al., 2004; Mey et al., 2016). Comprehensive reviews on solar receivers investigated since the 1980s have been given in Avila-Marín (2011), Gómez-García et al. (2016), and Ho (2017). A detailed one-dimensional analysis has been employed to argue that receiver geometry and materials still lack adequate optimisation for maximum thermal conversion efficiencies (Kribus et al., 2014).

It is shown in this paper that variable geometry open volumetric air receivers can address the main problems still encountered in these components (where the incident radiative heat flux is almost completely absorbed in the front region), and potentially operate under volumetric effect conditions. Receivers described here have been built from the structured repetition of elementary cells, leading to hierarchically-layered configurations of decreasing porosity levels. This allows for an enhanced diffusion of incident sunlight and a shift of radiation absorption profiles towards the rear, which reduces thermal emission losses. An additional advantage is the augmentation of internal convective heat transfer in the receiver through a combination of aerothermal mechanisms: a gradually increasing wetted area surface, a reduction of flow cross-sectional areas (increasing flow velocities, Reynolds numbers, and heat transfer coefficients), and the generation and enhancement of turbulent flow structures within the intricate flow channels. Flow instabilities observed in monolithic configurations (Pitz-Paal et al., 1997) can also be avoided due to the flow field redistribution variable geometry receivers allow for.

Some so-called fractal-like solar receivers have been recently proposed, not based on variable porosity concepts, but on the repetition of elementary structures at larger scales: the SCRAP receiver (Lubkoll et al., 2016), a pin-shaped external micro-structure (Capuano et al., 2017), a bladed receiver (Wang et al., 2016), and staggered rearrangements of tubes along self-repeating patterns (Ortega et al., 2016). The SCRAP receiver is a pressurised air receiver where numerous outward radial spikes are internally cooled by recirculating flow channels. The pin-shaped micro-structure is similarly spiked, but intended as a frontal add-on to current open volumetric air receivers. An experimental prototype was manufactured by additive manufacturing (electron beam selective melting) in Titanium-Aluminium alloy (Ti6Al4V) and showed promising initial results. The last two have been designed as improvements for current molten salt tubular receivers. All are aimed at enhancing light-trapping performance and move the operating point of solar receivers closer towards volumetric effect conditions by minimising emission losses. This paper presents a fully-integrated experimental assessment of some new fractal-like receivers, which show potential as candidates for the replacement of current monolithic honeycombs and foams.

2. Design and manufacturing of hierarchically-layered receivers

The development of variable geometry receivers built from the fractal repetition of elementary cells has been made possible by recent advances in additive manufacturing techniques. These allow for the design of creative highly-customised components based on complex geometries with improved functionality. Selective laser melting (SLM), which utilises a laser beam to melt successive layers of powder into a finished part, has been the manufacturing technique employed here. This technique was previously used to fabricate extremely compact heat exchangers for advanced thermodynamic power cycles (Crema et al., 2014).

Receivers were manufactured in AISI 316L stainless steel, but Inconel 625 components can also be produced. Porosity can be varied over a wide range of scales, the smallest pores achievable being approximately 0.1 mm in diameter. Convective heat transfer can be thus enhanced by employing, if required, augmentation features in this sub-mm scale. Additionally, variable porosity geometries allow thermal conduction to be geometry-driven (by adjusting solid cross-sectional areas and creating bottlenecks for the outward flow of heat) as well as material-driven. The work presented here aimed at the combination of these desired features into integrated optimised components, building on previous studies of hierarchically-layered geometries at the IMDEA Energy Institute (Gómez-García et al., 2015) and in bilateral collaboration with the Fondazione Bruno Kessler (Pratticò et al., 2017).

Components have been designed by applying fractal growth factors to a reference unitary element. The elementary cell consists of a right rhombic prism with partially open lateral walls, which permit flow redistribution between adjacent cells. All rhombi are parallelograms with adjacent angles equal to 60° and 120°. The elementary cell is laterally replicated to form a constituent layer. Finally, the hierarchically-layered absorber is built by stacking up several layers, each one composed of elementary cells of decreasing size. Variable porosity structures are thus achieved both by having layers of different