Solar Energy Materials & Solar Cells 140 (2015) 382–387

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Tubular Si-infiltrated SiC_f/SiC composites for solar receiver application – Part 2: Thermal performance analysis and prediction

A. Ortona [a], D.H. Yoon [b], T. Fend [c],*, G. Feckler [c], O. Smirnova [c]

[a] ICIMSI, SUPSI, Galleria 2, CH-6928 Manno, Switzerland
[b] School of Materials Science and Engineering, Yeungnam University, Gyeongsan 712-749, Republic of Korea
[c] Institute of Solar Research, German Aerospace Center, Linder Höhe, 51147 Köln, Germany

ARTICLE INFO

Article history:
Received 24 September 2014
Received in revised form
18 March 2015
Accepted 21 April 2015
Available online 15 May 2015

Keywords:
Hybrid engineered ceramics
Solar gas turbine
Heat transfer performance

ABSTRACT

Tubular Si-infiltrated SiC_f/SiC composites composed of an inner cellular ceramic and an outer dense Ceramic Matrix Composite (CMC) skin have been fabricated by the electrophoretic deposition of matrix phases followed by Si-infiltration for pre-feasibility testing in solar receiver applications. The tubes have been considered to be used as high temperature receiver components for the solar operation of a gas turbine or a combined cycle with temperatures up to 1300 °C and typical pressures of more than 6 bar. The cellular structure inside the tube has been introduced for the improvement of heat transfer from the irradiated outer surface of the tube to the working fluid inside. Heat transfer and permeability characteristics of the composite samples have been determined experimentally as effective properties. These properties have been used in numerical models to predict the performance of such kind of components in gas turbine service conditions. It could be demonstrated, that the heat transfer rate in a tube with a porous in-lay could be increased to approximately four times compared to the rate of an empty tube of the same size. The results of the study give reason for further experimental testing in service environments.

1. Introduction

Due to beneficial thermal properties, the use of Si-infiltrated SiC fiber-reinforced SiC ($SiC_f/Si/SiC$) composites offers great chances for a significant improvement of high temperature components such as heat exchangers, recuperators, solar receivers and many more. In nearly all of these applications, high temperature strength, thermal shock resistance, large thermal conductivities and large specific surfaces for heat transfer are needed [1].

The present study is focused on the application as a tubular high temperature receiver for the solar gas turbine [2]. This component is aimed at being placed in the focus of a *Solar Tower*, a large scale installation to generate electricity from concentrated solar radiation, where it is operated at typical temperatures of 1200–1300 °C [3].

The principle concept of a solar driven gas turbine or a solar driven combined cycle has been already proposed earlier [4–6]. In the recent past, small systems have been also considered with the advantage of a simpler secondary use of the waste heat [7,8]. The main motivation for the interest in the gas turbine and the combined cycle is its high efficiency compared to other thermal engines.

From the options for a solar operation of a combined cycle in Fig. 1, only option 2 offers high solar shares such as more than 90% or even a "solar only" operation, which would also enable to leave out the topping combustor and replace it with a thermal storage system.

The tubular receiver is a bi-functional component employed to absorb radiation (up to 1000 kW/m²) and to transfer heat to a working fluid, in case the gas turbine is operated by hot pressurized air. How it principally could look like is shown in Fig. 2 [13]. It also shows the main drawback of a tubular solar receiver, which is the convective thermal resistance during the heat transfer from the solid wall to the gas.

To overcome this drawback and to enable high application temperatures, a new tubular receiver has been proposed for this study, which follows a hybrid concept. The tube wall is based on a Ceramic Matrix Composite (CMC). It is connected to a ceramic porous in-lay made from reticulated foam or an engineered porous 3D-structure. By increasing the overall heat transfer surface and by minimizing the characteristic diameter representative for the flow through the open pore system of the structure, the heat transfer is considered to be increased significantly. The principle concept of this approach is shown in Fig. 3.

The objective of the study is to pre-qualify the material technology considered for a possible application in solar gas turbine environments.

---

* Corresponding author. Tel.: +49 2203 601 2101.
E-mail address: thomas.fend@dlr.de (T. Fend).

http://dx.doi.org/10.1016/j.solmat.2015.04.034
0927-0248/

Nomenclature

A_V	specific surface area [1/m]
C_p	specific heat capacity [J/(kg K)]
d_{ch}	characteristic length [m]
K	permeability coefficient [m]
k_{eff}	effective thermal conductivity (porous medium) [W/(m K)]
k	thermal conductivity (solid) [W/(m K)]
k_{fluid}	thermal conductivity (fluid) [W/(m K)]
K_1	viscous permeability coefficient [m²]
K_2	inertial permeability coefficient [m]
l	length [m]
$\dot{m}$	mass flow rate [kg/s]
n	normal vector [dimensionless]
q_0	heat flow rate [W/m²]
P	pressure [Pa]
Q	power [W]
T	fluid (air) temperature [K]
T_{in}/T_{out}	fluid temperature (in- and out-let) [K]
T_2	solid temperature [K]
T_w	wall temperature [K]
u	flow velocity [m/s]
V	volume [m³]
α	heat transfer coefficient [W/(m² K)]
ΔT_{log}	log. Temperature difference [K]
ε_P	porosity [dimensionless]
η	dynamic viscosity [Pa s]
ρ	density [kg/m³]

The materials investigated in this study were tubular samples consisting of tube walls, which have been manufactured from Si-infiltrated SiC fiber reinforced SiC (SiC_f/Si/SiC) and porous in-lays made out of highly cellular siliconized SiC foam (Engicer SA, Balerna, CH). Additionally and for comparison, an alternative in-lay made from a determined 3-D structure was used, which was based on a printed polymer pre-form. The processing of the samples has been already described in more detail in a prior publication [9].

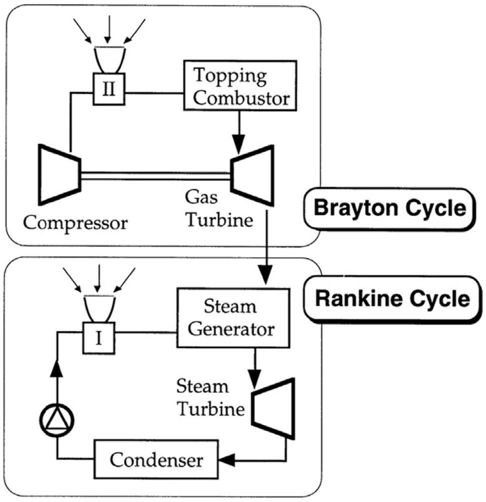

Fig. 1. Options for a solar operation of a combined cycle [4].

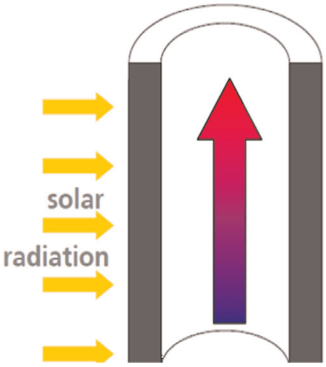

Fig. 2. Principle of a tubular high temperature receiver for solar tower technology.

2. Methodology

To predict the behavior of the proposed material technology in real service conditions a three-stage approach has been chosen. In the first step, heat transfer and permeability characteristics have been determined experimentally at ambient pressure and temperature below 100 °C. Secondly, a 2-D CFD-model has been developed for the experiment to determine the volumetric heat transfer coefficient by means of a parameter study. Finally, along with the acquired permeability coefficient this quantity was used to transfer the numerical model to high pressure and high temperature conditions.

2.1. Samples investigated and experimental set-up

From the test samples manufactured at the labs of SUPSI and Yeungnam University and delivered to DLR, four have been taken for testing. Two of the "foam in-lay"- type and two of the "3D-printed in-lay"-type (Fig. 4). The samples dimensions are 20 mm

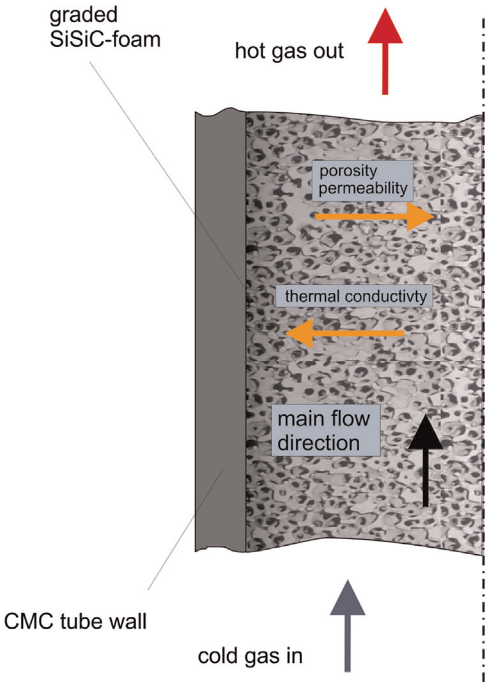

Fig. 3. The concept of the present study: CMC tube wall and enhanced heat transfer with a porous in-lay.