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Numerical investigation of flow and heat transfer in a volumetric solar receiver

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ABSTRACT

Volumetric solar receivers are used in solar power plants to convert concentrated solar radiation into high temperature heat to operate a thermal engine. In general, porous high temperature materials are used for this purpose. Since the pore geometry is important for the efficiency performance of the receiver, current R&D activities focus on the optimization of this quantity. In this study, the influence of slight geometry changes of this component on its temperature distribution and efficiency has been investigated with the objective of an overall improvement. A numerical analysis of the mass and heat transfer through the receiver has been performed. The investigated receiver was an extruded honeycomb structure made out of Silicon Carbide. Additionally, experimental tests have been performed. In these tests, selected receiver samples have been exposed to concentrated radiation. From these tests solar-to-thermal efficiency data have been derived, which could be compared with the calculated data. Two numerical models have been developed. One makes use of the real geometry of the channel (single channel model), the other one considers the receiver to be “porous continuum”, which is described by homogenized properties such as permeability and effective heat conductivity. The experimental parameters such as the average solar heat flux and the mass flow were taken into account in the models as boundary conditions. Various quantities such as the average air outlet temperatures, the temperature distributions and the solar-to-thermal efficiency were used for the comparison. The correspondence between the experimental and numerical results of both numerical models confirms the capability of the approaches for further studies.

1. Introduction

The volumetric solar receiver is one of the key components of *solar tower technology*, which uses concentrated solar radiation to generate thermal energy to operate a thermal engine. The concentrated radiation is generated by a large field of individually moving mirrors (heliostats). The focus is located on top of a tower (Fig. 1, left). The receiver, located in the focus, generally consists of a porous material, which absorbs the radiation and transfers it into heat of an air flow. After that, the air is used to generate heat in a boiler.

A reliable, continuous and predictable operation of the solar receiver is of great importance. It has been investigated already since 1985. From this time, numerous studies have been published [1–4]. A comprehensive review is given in Ref. [5]. The material investigated is an improved Silicon Carbide honeycomb structure based on the state-of-the-art-technology shown in Fig. 1 (middle and right), which has also been applied in the solar tower in Jülich [6]. It has been manufactured by St. Gobain IndustrieKeramik Rödental.

In the current study, the performance of one single receiver module has been investigated experimentally and numerically. The numerical work was carried out using two different models of the volumetric solar receiver. The first of them, the so called “single channel model” describes air flow and heat transfer in a selected volume in detail and the second one (“continuum model”) describes air flow and heat transfer in the whole volume of the module treating the absorber as a porous medium described by effective properties.

In the numerical work presented, the influence of geometrical variations on the overall performance of the receiver was investigated with the objective to further increase the efficiency of this component. The geometry of the receiver modules can be seen in Fig. 1. They consist of a honeycomb-like ceramic structure made out of channels and walls named “absorber”: This absorber is embedded in a ceramic containment, the so-called “cup”. Two geometrical

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Nomenclature

A	inlet surface of the receiver, m^2
A_V	specific surface, m^2/m^3
C_P	specific isobaric heat, J/(kg K)
C	emissivity·Stefan Boltzmann constant, $W/(m^2 K^4)$
I	radiative flux density, W/m^2
K	permeability, m^2
k	thermal conductivity, W/(m K)
$\dot{m}$	mass flow rate density, $kg/(s\ m^2)$
$\dot{M}$	mass flow rate, kg/s
Nu	Nusselt number, –
p	pressure, Pa
Q	power, W
q	power per unit volume, W/m^3
q_0	solid/fluid convective heat exchange, W/m^3
Re	Reynolds number, –
T	air temperature, K
T_2	solid temperature, K
u	velocity, m/s
z	coordinate along the main flow direction, m

Greek symbols

α	convective heat transfer coefficient, $W/(m^2 K)$
η	coefficient of the dynamical viscosity, kg/(m s)
ε_p	porosity, –
ρ	density, kg/m^3
ξ	extinction coefficient of the radiation, 1/m
φ	inlet angle of the radiation flow, °
ε	emissivity, –
γ	reflectivity

Indices

rad	radiative
abs	absorptive
0	located at the irradiated front surface (radiative flux density)
inlet	located at the irradiated front surface (entrance of the air flow into the absorber)
outlet	located at the outlet of the air flow from the absorber

variations have been chosen for the investigations in this study. The first one considers two different channel diameter/wall thickness dimensions and the second one considers the overall shape of the absorber.

2. Methodology

2.1. Experimental set-up

To investigate performance characteristics of the receiver, a tubular experimental set-up was used, which was able to supply boundary conditions similar to the application in the power plant for one 140*140 mm receiver module. Fig. 2 shows a photograph of the whole set-up, Fig. 3 shows the flow scheme. The receiver cup is plugged into a high temperature steel tube, which was insulated with high-temperature-materials based on ceramic fibers. The concentrated radiation of up to 900 kW/m^2 is provided by 10 Xenon short-arc lamps with ellipsoid reflectors. As ellipses have two foci, the short arc lamps are located in the first focus as emitters, the sample is located in the second focus. The distance between the lamps and the sample is approximately 150 cm.

The concentrated radiation meets the inlet surface of the receiver sample and heats it up. The blower supplies the pressure difference and causes an air flow through the sample. Thus cold ambient air is heated up to defined temperatures, which are measured with thermocouples at the locations shown in Fig. 3. At each location at least 3 thermocouples were used. The test bed can be used for tests with and without air return flow. For the purpose of the current study, no return air flow was used, because the capability of the material to convert radiation into heat should be tested. A counter flow air/water heat exchanger was used to cool down the air temperature to protect the following components (mass flow meter, blower) from high temperatures. Furthermore the determination of the absorbed energy is easier and more precise if the enthalpy gain of the water circuit is measured. Besides air and water temperatures also flow rates of water and air are measured and logged with a standard pc-based data acquisition system.

Additionally, radiation flux and surface temperature are measured with separate devices. For the radiation flux, the camera-target system FATMES with an accuracy of ±5% is employed [7]. Surface temperature has been monitored with standard infrared thermography.

Efficiency is calculated according to equation (1):

$$\eta = Q_{abs}/Q_{rad} \tag{1}$$

Here, Q_{rad} is the irradiative flux from the lamps penetrating onto the aperture of the sample. It has been determined by integrating

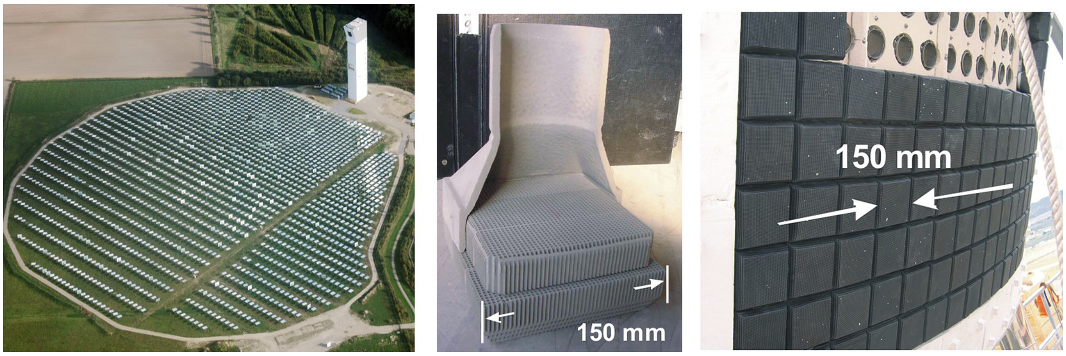

Fig. 1. Photographs of the Jülich Solar Tower (left), a part of a single absorber module and the solar receiver during installation.