Solar Energy 146 (2017) 351–358

Contents lists available at ScienceDirect

Solar Energy

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

Air return ratio measurements at the solar tower Jülich using a tracer gas method

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ARTICLE INFO

Article history:
Received 15 August 2016
Received in revised form 12 January 2017
Accepted 18 February 2017
Available online 9 March 2017

Keywords:
Air return ratio
Tracer gas
Solar tower Jülich
Solar air receiver
Air receiver
Measurement technique
Dynamic mass spectroscopy

ABSTRACT

The air return ratio is a key factor for the overall efficiency of the open volumetric receiver concept. Although first measurements of the air return ratio exist for smaller setups of the open volumetric receiver concept, so far no measurement of the air return ratio has been presented for the Solar Thermal Test and Demonstration Power Plant Jülich ($\approx$1.5 MW, $\approx$10 (kg air)/s; $\approx$700 °C). This paper describes the application of a tracer gas method at the solar tower Jülich to determine this substantial ARR.

As tracer gas the environmentally friendly helium has been chosen. The helium is injected dynamically into the circular air flow of the system and the helium mole fraction is measured using a mass spectrometer. The dynamic concentration response of the system is used to determine the air return ratio. This dynamic method only requires one location of measurement. First measurements with this dynamic method were conducted at the solar tower Jülich. The ARR of STJ was measured with and without irradiation of the main receiver with high accuracy.

Under low-wind conditions and without irradiation of the main receiver the air return ratio was measured to be $(67.7 \pm 0.5)\%$ for an air mass flow of (9.96 ± 0.04) kg/s. A slightly higher air return ratio of $(68.6 \pm 0.7)\%$ was measured under irradiation with an air mass flow of (9.94 ± 0.04) kg/s. The air return ratio was sensitive to the air mass flow, showing significantly lower rates when moving further away from the 10 kg/s design air mass flow to 5 kg/s.

1. Motivation and background

Concentrated solar power provides an environmentally friendly and virtually unlimited source of high-temperature heat (Romero and Steinfeld, 2012). This heat can be converted into electricity, stored or used as process heat for industrial processes. Since this process heat can be stored, concentrated solar power is considered to be a stable renewable energy source.

The heat is generated by concentrating sunlight using mirrors onto a solar receiver where the radiant energy is absorbed and transformed into thermal energy. This energy can be transported using various heat transfer fluids and can be stored until further use. Central receiver systems have a high potential due to an increase in the achieved temperature (Romero and Steinfeld, 2012). Additionally, central receiver plants are the most resource-efficient ones (Samus et al., 2013). The commonly used thermal fluids in the receiver are saturated or superheated steam and nitrate-based molten salts. These are usually pipe receivers, whereby the solar radiation is absorbed on the outer surface of the piping. This causes the maximum temperature to be located at this point. In the volumetric receiver concept, the solar radiation can penetrate into the material. This theoretically allows that the outer temperature is lower than the maximum temperature due to cooling. This is the so called volumetric effect. This concept could allow a more efficient solar energy capture and conversion (Romero and Steinfeld, 2012).

It was realized at the solar tower Juelich (STJ) in 2008 with a field of 2153 heliostats. These reflect and concentrate the sunlight onto an open volumetric receiver at the top of the 60 meter high solar tower power plant. The receiver consists of a porous ceramic structure of modular design to allow for scalability. It comprises of 1080 absorber modules (see Fig. 1B) which make up the receiver (see Fig. 1C). By absorbing the sunlight the front of this receiver is heated to around 700 °C (Andlauer, 2015). As heat transfer fluid air is sucked through the absorber modules to transport the thermal energy to a heat exchanger or storage unit. Due to the low heat capacity of air, high air mass flows are required.

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http://dx.doi.org/10.1016/j.solener.2017.02.027
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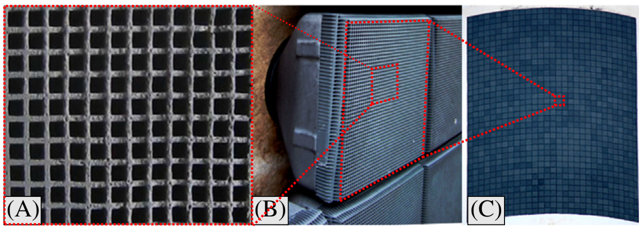

Fig. 1. The receiver of the solar tower Juelich. (A) shows a close up of the absorber structure of the Hitrec-II absorber module, (B) individual absorber modules during maintenance which make up the main receiver of the solar tower Juelich (C).

To increase efficiency a fraction of the blown out air is sucked in again. This fraction is the substantial air return ratio (ARR) which is defined by Ahlbrink et al. (2013) as

$$ARR = \frac{\dot{m}_{\text{return}}}{\dot{m}_{\text{out}}}. \tag{1}$$

Hereby $\dot{m}_{\text{out}}$ is the air mass flow blown out in between the absorber cups, and $\dot{m}_{\text{return}}$ is the part of this air which is sucked in again into the air circuit. Ideally, the ARR would be 100%. In addition to the substantial ARR, Maldonado Quinto (2016) defines a thermal ARR at the receiver surface as

$$ARR_{\text{thermal}} = \frac{\dot{m}_{\text{in,rec}} \cdot (h_{\text{in,rec}} - h_{\text{amb}})}{\dot{m}_{\text{out,rec}} \cdot (h_{\text{out,rec}} - h_{\text{amb}})}, \tag{2}$$

whereby $h_{\text{out,rec}}$ is the specific enthalpy of the blown out air, $h_{\text{in,rec}}$ of the sucked in air and h_{amb} of the ambient air. The reason for defining ARR_{thermal} is to calculate the overall efficiency of the power plant. A schematic of the air flow within the receiver is shown in Fig. 2. The points at which the above used enthalpies are defined, are indicated. The thermal ARR and hence especially the specific enthalpies and mass flows are defined at the surface of the receiver. If the small losses of the return air enthalpy due to conduction and gas emission of air are neglected, the thermal ARR turns into the substantial ARR (Eq. (1)) when defined at the receiver surface (Maldonado Quinto, 2016)

$$\dot{m}_{\text{return,rec}} \approx \dot{m}_{\text{in,rec}} \cdot \frac{(h_{\text{in,rec}} - h_{\text{amb}})}{(h_{\text{out,rec}} - h_{\text{amb}})}. \tag{3}$$

The measurement of this substantial ARR is discussed within this paper.

To improve the receiver efficiency it is important to increase the ARR and therefore minimize the occurring leak within the air circuit. At a receiver air output temperature of 650 °C an improvement from an $ARR = 60\%$ to $ARR = 80\%$ causes an increase in 8 percentage points of the normalized system efficiency (Maldonado Quinto, 2016). The ARR is so far unknown on a large scale and under solar irradiation. Since it can be influenced by a multitude of measures as for example wind speed and direction, it is of vital importance to be able to measure it (Storch et al., 2015; Vogel and Kalb, 2010).

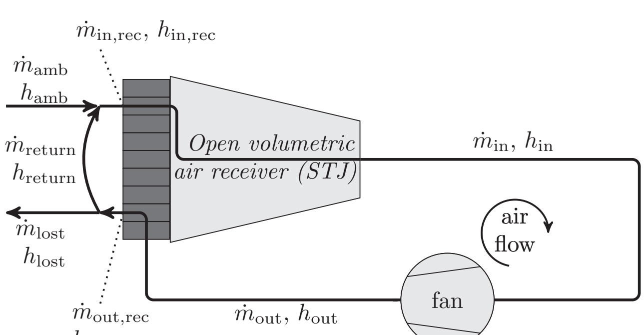

Fig. 2. A schematic of the open volumetric receiver is shown. The air mass flows $\dot{m}$ and specific enthalpies h are indicated.

2. Solar tower Juelich

The Solar Thermal Test and Demonstration Power Plant Juelich (STJ) was built as a demonstration as well as research power plant in 2008 by a consortium consisting of the German Aerospace Center (DLR), Solar Institute Jülich, Kraftanlagen München GmbH and Stadtwerke Jülich. It was taken over by the DLR in 2011 (Koll et al., 2009). In Fig. 3 a photo of the 60 m high solar power tower is depicted. The main receiver (A) as well as the Testreceiver (C) can be seen. These two receivers can be irradiated by reflecting and concentrating sunlight with 2153 heliostats onto their surface. The heliostats make up a combined total surface of nearly 18000 m^2 (Funken, 2013). Their back structure can be seen in (D).

The main receiver covers a surface area of around 22 m^2. It has the shape of a section of a cylinder and is inclined downwards towards the heliostats. It consists of 1080 ceramic absorber modules through which air is sucked in and heated to a temperature of about 680 °C. This hot air can be sucked through the thermal storage system consisting of a large vessel filled with porous ceramic bricks or directly through the steam boiler. The steam is generated in a heating tube boiler, which is further used to drive a turbine and produce electricity (Koll et al., 2009). After passing the thermal storage or the steam boiler, the air is returned to the receiver front. Here it is blown out through the gaps between the absorber modules. This is depicted schematically in Fig. 5.

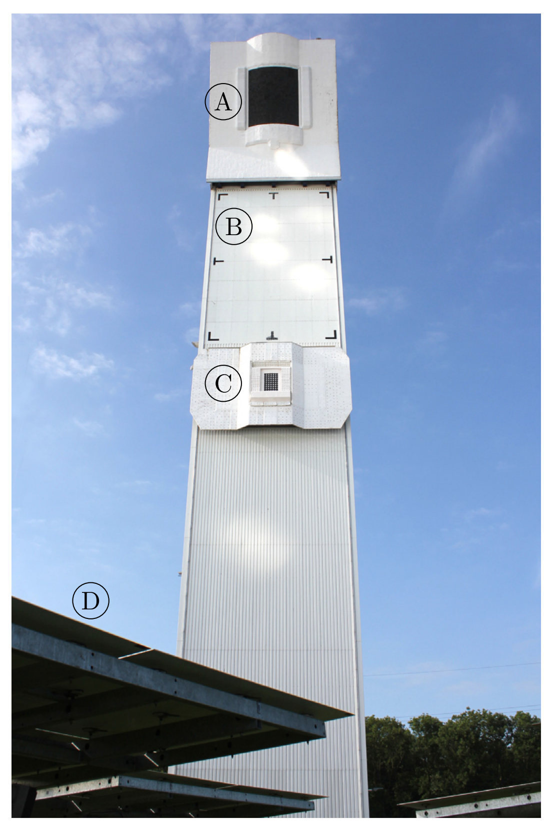

Fig. 3. Photo of the STJ displaying the main receiver (A) at the top, the target for the calibration of heliostats (B), the Testreceiver (C) and the heliostats (D) at ground level.