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Induced Infrared Thermography: Flow visualizations under the extreme conditions of an open volumetric receiver of a solar tower

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ABSTRACT

Current measurement techniques do not allow the visualization of the return air flow of open volumetric receivers in solar tower power plants. The reason is that the region of interest is irradiated by concentrated solar radiation and is located on top of a tower. Therefore, a novel method of measurement, the Induced Infrared Thermography (IIT) is introduced within this paper. With this method the return air can easily be observed with an infrared camera. As air has a very low emissivity in the infrared region the activity has to be induced by the addition of an infrared-active component, here carbon dioxide. The temperature of the infrared-active component has the greatest influence on the signal strength but the mole fraction of the component and the distance to the infrared camera are also important. Due to temperature restrictions, the measured signal to noise ratio is low and therefore several post-processing steps have to be conducted to visualize the return air. The most important step for the visualization is subtracting a background image. Furthermore, a video filter is employed in order to remove noise. A time series of ITT images can be used to obtain information on the velocity fields of the flow. The process, called Infrared Image Velocimetry (IRIV) here, is similar to Particle Image Velocimetry (PIV) and is applied in this paper to external fluid flows of the open volumetric receiver. As IRIV is in an early stage of development the depicted results are treated as qualitative vector fields.

1. Introduction

High levelized energy costs are one of the main problems of current renewable power generation techniques. Besides photovoltaics, concentrated solar power (CSP) is a promising technology using solar radiation especially due to the possibility of using cost-efficient heat storages (Sargent & Lundy LLC Consulting Group, 2003; Pitz-Paal et al., 2003). Among existing CSP-technologies solar power towers are expected to yield the lowest levelized energy costs (Pitz-Paal et al., 2003).

There are several types of solar tower power plants that have the potential to be commercially implemented in the future (Romero et al., 2002). One of these types is the open volumetric air receiver, as realized in the Solar Tower Jülich (STJ). In this technology air is sucked into and heated by the receiver, which is the target of concentrated solar radiation. Then the thermal energy of the air is used to power a conventional Rankine cycle. After the heat exchange in the steam boiler or a heat storage the air still has temperatures of up to 200 °C. It is returned to the receiver to cool the structure and to utilize the remaining heat by mixing with or replacing the ambient air that is sucked into the receiver. The schematic of the STJ is displayed in Fig. 1. For a high efficiency of this type of solar towers it is crucial to suck in most of the exhausted air. The fraction of air that is sucked back into the receiver per air ejected out of the receiver is called Air Return Ratio (ARR) (Koll et al., 2009; Alexopoulos and Hoffschmidt, 2010).

Previous studies (Tiddens et al., 2015) have shown a way to determine the ARR by injecting a tracer gas and measure the concentration difference between the receiver outlet and inlet. Currently the ARR at the STJ is in the range of 67–69% (Tiddens, 2016), but it should be at least 80% to be competitive, especially for higher return air temperatures in the future (Marcos et al., 2004; Vogel, 2010).

The ARR is a good measure of the overall air recovery performance. It yields however little information about concrete improvement possibilities, e.g. other receiver geometries, cavities or different operating parameters. Therefore, visualization and determination of the flow field might be helpful. The flow field could be measured or visualized by traditional techniques such

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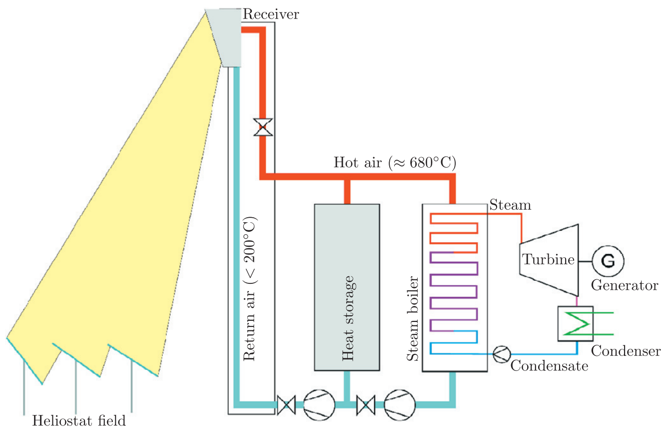

Fig. 1. Functional principle of open volumetric receiver solar tower power plants. Solar radiation is concentrated by a heliostat field onto a receiver. Ambient air is sucked into the porous receiver and heated up to 680 °C. The heated air can then be used either to power a Rankine cycle or to heat a thermal storage. The return air is ejected through the receiver to cool the structure and is partly sucked back into the receiver to utilize the return air with a remaining temperature of up to 200 °C. Based on Funken (2013).

as Particle Image Velocimetry (PIV) or the more recently developed Background Oriented Schlieren (BOS). Although these techniques were successfully demonstrated in other experiments (e.g. see Westerweel, 1993 or Raffel et al., 2000), an application on the large scale of solar towers is difficult.

Moreover, a simulation using CFD is only possible for parts of the tower in acceptable computational times. For instance, Maldonado Quinto (Maldonado Quinto, 2016) simulated up to four out of 1080 absorber modules and validated the results with PIV in a test rig.

Within this paper a simple, novel measurement technique, the Induced Infrared Thermography (IIT) is introduced. Hereby the commonly used infrared thermography is enhanced by injecting an infrared-active gas, i.e. an IR-tracer into the gas flow which is subsequently measured. Without the injection of the IR-tracer the use of infrared thermography for gases that are not active in the infrared would not be possible. The thermal radiation of the IR-tracer is then detected by an infrared camera in the form of an image which is the result of the IIT. IIT-images e.g. yield the possibility to easily check for leakages or to compute a flow field. The latter can be achieved by a technique we named Infrared Image Velocimetry (IRIV) (Tiddens and Röger, 2015) that is similar to PIV. IRIV is in an early stage of development and described in Section 3.3.

2. State of the measurement technology

The return air flow is large (about 10 kg/s) and it is open to the environment. The ejected return air must be visualized in front of the receiver, which is a harsh environment as it is the target of highly concentrated solar radiation. Due to the radiation no direct flow measurement devices, like pressure probes, can be easily utilized. Therefore, optical measurement methods must be used.

One option is the usage of PIV by adding particles. But it is difficult to seed particles homogeneously into such a large air flow. Furthermore, in PIV-experiments usually a certain plane is illuminated by a laser and the flow in this plane is analyzed. Illuminating only a certain plane is difficult for a solar tower as a high powered laser would be required in order to overshine the particle reflections of the concentrated solar radiation. Finally, particles are unwanted in the system and the environment. So measurement techniques that are based on particles are not further regarded for our application.

Table 1
Different measurement techniques and their suitability for a return air visualization.

Type of measurement Measurement technique	suitable?
Velocity	
Pressure Probes	no, point meas.[a]
Hot-Wire Anemometer	no, point meas.[a]
Pulsed Hot-Wire Anemometer	no, point meas.[a]
Tracer	
Laser Doppler Anemometry (LDA)	no, point meas.[a]
Laser Flash Analysis (LFA)	no, point meas.[a]
Particle Image Velocimetry (PIV)	no, particles unwanted
Particle Tracking Velocimetry (PTV)	no, particles unwanted
Laser Surface Velocimetry (LSV)	no, particles unwanted
Droplet Tracking Velocimetry (DTV)	no, point meas.[a]
Molecular Tagging Velocimetry (MTV)	no, high laser output
Refractive Index	
Background Oriented Schlieren (BOS)	hardly, high cnstr.[b] effort
Laser Speckle Photometry (LSP)	no, high cnstr.[b] effort
Schlieren PIV	hardly, high cnstr.[b] effort
Shadowgraph	hardly, high cnstr.[b] effort
Interferometry	no, line measurement
Infrared Radiation	
IR-Thermography	no, air is hardly IR-active
Induced Infrared Thermography (IIT)	yes

[a] meas.: measurement
[b] cnstr.: construction

The remaining temperature of the return air could be utilized for the visualization as the refractive index of air differs with the temperature. Compared to the ambient air the return air has a different refractive index resulting in a distortion of the background in areas where the return air is present. These distortions are called Schlieren. In the background oriented Schlieren method (BOS, see e.g. Raffel, 2015) a density gradient field is calculated by the optical displacement of a dotted background image due to these Schlieren. Because of the radiation and the height of the receiver of about 60 m it is quite complex to install such a background image. Alternatively, Raffel et al. (2014) demonstrated the use of the natural background, hence avoiding installation efforts. The refractive index of the air in front of a camera is calculated via the changes of structures, e.g. trees, in the natural background. At the STJ the ground would be the natural background so that the camera must be mounted on the top of the solar tower and therefore needs radiation protection, resulting in a high constructional effort for this particular application.

Infrared thermography is commonly used in heat transfer measurements. It is however rarely used for the visualization of gas flows. Gordge and Page (1993) use infrared imaging to investigate a subsonic, non-isoenergetic air/carbon dioxide axisymmetric jet. Yoon et al. (2006) use pure heated carbon dioxide in walk-through portal detection systems to screen passengers for the presence of explosives. In industry, so called optical gas imaging cameras are used to localize gas leaks in factories.

For the visualization of a poorly infrared-active gas, an infrared-active component can be added to the flow which is to be examined. The active gas can then be detected by an infrared camera. Narayanan et al. (2003) introduced this technique on a lab scale by using sulfur hexafluoride (SF_6) to visualize the air flow of a free impinging and reattachment subsonic air jets in the range of 8–13 μm. Table 1 summarizes the suitability of several measurements techniques for the use at the STJ.

3. Theory of IIT and IRIV

3.1. Choice of gas for Induced Infrared Thermography (IIT)

As previously stated, an infrared-active component has to be added to the air flow to enable the visualization via infrared