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A tracer gas leak rate measurement method for circular air circuits

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ABSTRACT

Qualitative measurements of leaks in air flows are frequently conducted in engineering. However, an environmentally friendly leak rate measurement technique which yields quantitative results and is applicable to hot, large-scale circular air flows (≈ 10 kg/s; $\approx$ 700 °C) with high leak rates has not been presented yet. This paper describes the development, test and validation of a stationary and a dynamic, helium based tracer gas method on a lab-scale model of a solar air receiver with partial air recirculation. Helium is chosen as tracer gas since it is environmentally friendly, stable under high temperatures and is also cheap for large-scale air flows. The tracer gas is injected either continuously or intermittently into the model system, its concentration is measured using a mass spectrometer and the static or dynamic concentration response of the system is used to determine the leak rate. The stationary method needs two measurement points upstream and downstream the leak, the dynamic method only one measurement point if applied to a circular air flow system. Since the dynamic method is time dependent the transfer function of the measurement setup was determined and the dynamic measurement error was considered. An extensive uncertainty analysis is presented for both the stationary and the dynamic method. Exemplary measurements were conducted at the model system with very good results. Both dynamic and static measurements yield the same result within their confidence intervals. The leak rate of the solar receiver model with a mass flow rate of $\dot{m}_{in} = (0.247 \pm 0.008)/\mathrm{kg\,s}$ was measured to be $l_{\mathrm{stat}} = (36.1 \pm 2.3)\%$ and $l_{\mathrm{dyn}} = (34.5 \pm 3.6)\%$ with the static and the dynamic method respectively.

1. Introduction

Concentrated solar energy provides an environmentally friendly and virtually unlimited source of high-temperature heat [1]. As in most renewable energy research, cost reduction is the main research goal. It is therefore essential to quantify all factors that influence the efficiency of energy production. The examined open volumetric receiver concept was build on a large scale as the Solar Tower Jülich demonstration solar power plant [2]. Here the sunlight is reflected and concentrated by a field of heliostats onto an open volumetric air receiver. This open volumetric receiver consists of a porous ceramic structure which is heated up by absorbing the sunlight creating surface temperatures of up to 1000 ° C. Air is sucked through the absorber modules to transfer the thermal energy to the steam boiler, where a conventional power block is used to produce electricity. Due to the low heat capacity of air, high air mass flows are needed. After the air passes the steam boiler, it has a temperature of up to 200 ° C and is returned to reuse the residual heat. It is blown out through the structure of the receiver and is partially sucked in again. The fraction of the blown out air, which is sucked in again, is called air return ratio (ARR) (Eq. (1)). At this point the examined leak of the system occurs.

To achieve a high receiver efficiency it is important to decrease this leak in the air circuit. It depends on many variables such as wind, geometry of the receiver design and operational mode and is so far unknown. Since this leak can be reduced by a multitude of measures, it is of vital importance to be able to measure it [3,4].

The leak rate measurement can be approached either by measuring the mass flow field in front of the receiver, or measuring the temperature or a chemical property of the air before and after the leak which changes according to the size of the leak. To measure the air flow field in front of the receiver the measurement technique needs to be applicable with very high precision. However, most flow measurement techniques are not employable on the large scale of solar tower power plants or do not yield quantitative results. An existing and possibly the most feasible flow measurement is the laser based Particle Image Velocimetry (PIV). It would be possible on such a scale, however resulting in large uncertainties.

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Due to the difference in temperatures before and after the receiver, caused by the leak of the system, an energy balance seems possible measuring only the air flows and their temperature. On the outside of the receiver this measurement is not feasible, since for a measurement of the air flows and their temperature thousands of thermocouples and mass flow measurements would be needed. A measurement in the airflow before and after the receiver as conducted by Tellez et al. [5] does not lead to correct results, since the outlet temperature is not well defined. This occurs because the outlet air is heated by the outsides of the absorber cups while it is blown out [6].

Due to the above-mentioned difficulties, we decided to use a tracer gas method, whereby a tracer gas is injected and measured in the air flow. This is the only possibility, since all other measurable, intrinsic properties of the air are correlated to the temperature.

Tracer gas measurements are widely used in medicine, in ventilation experiments for buildings and air conditioning systems. Inert tracer gas washout tests are for example used to perform extended lung function tests [7]. In contamination experiments Tang et al. [8] use a tracer gas to simulate the spreading of diseases in hospitals. Contaminations in sewers are investigated by Lepot et al. [9] using a Rhodamine WT tracer. Similarly the spreading of hot or cold air is quantified in buildings [10]. For example Ghazi and Marshall [11] use a carbon dioxide tracer gas to determine and characterize leaks across windows, Cui et al. [12] use a decay rate method to determine the air change rate of buildings. These measurements however are not transferable to the described measurement environment, due to the harsh conditions at the Solar Tower Jülich. The high circular air mass flows with large leak rates do not allow for any gases already present in air or environmentally harmful gases. The occurring surface temperatures further limit the possible tracer gas candidates. The commonly used SF_6 can for example only be heated without decomposition up to 500 °C in the absence of catalytic metals and has furthermore the highest global warming potential of all gases [13,14]. Goldsworthy et al. [15] use a helium tracer to measure the flow rate of large ducted gas flows under harsh conditions, however do not measure leaks or examine circular flows.

For development and validation purposes, we constructed a 1:2 scale model of a subreceiver (56 absorber modules) and the corresponding air circuit of the Solar Tower Jülich (1080 absorber modules). The circular nature of the measurement environment permits additionally to the static measurement a dynamic measurement. The latter allows a quantitative leak rate measurement with just one dynamic tracer gas concentration measurement. By comparison of the static and dynamic methods, a validation of the methods of measurement at a laboratory scale can be achieved. This paper describes the development, application and validation of the two tracer gas methods.

2. Experimental set-up

A model of a part of the open volumetric receiver structure has been built to develop, test and validate the measurement setup without solar irradiation. It is a model of the open volumetric receiver containing 9×6 absorber cups at a scale of 1:2. Its schematic is shown in Fig. 2, a photo in Fig. 1.

The air is sucked through the receiver (6) by a fan (10) and is then returned to the receiver front through 13 air return tubes (8). The model is designed regarding the theory of similarity, to produce a flow pattern in front of the receiver similar to that of the Solar Tower Jülich. Due to the smaller size, modifications to the air circuit are simpler than at the full scale solar power plant. The fan can be operated at different rates to control the air mass flow. The air mass flow is measured to allow the measurement with different air mass flow rates by a thermal flow mass sensor (5). The sensor has been calibrated by the manufacturer, using a wind tunnel. It has been calibrated for the range of 0.0–26.6 Nm/s, using a pipe diameter of 146 mm. In Fig. 1 the piping can be seen, which ensures a homogeneous air flow at the point of measurement. The receiver can be covered by a removable lid (7), to test for unwanted leaks. By closing the receiver and removing some of the 13 return air tubes, different scenarios with fixed, unknown leak rates can be created for validation purposes (Section 4.3).

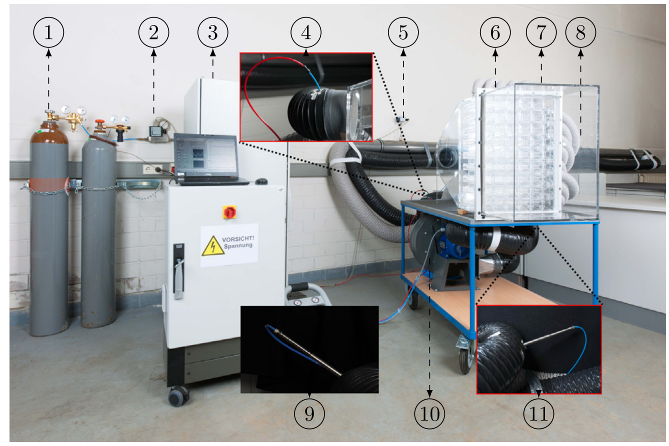

Fig. 1. Photo of the measurement setup, showing: (1) helium, (2) mass flow controller, (3) mass spectrometer, (4) helium injection, (5) air mass flow meter, (6) receiver, (7) removable lid, (8) air return tubes, (9) point of measurement, (10) fan, (11) point of measurement.

To conduct a tracer gas measurement, helium (1) is injected into the system at (4). The helium mass flow is controlled using a mass flow controller (2). The resulting helium concentration is then measured by extracting a sample at either point of measurement (9) and (11). Due to the choice of helium as tracer gas (see Section 3.1) and the low concentrations that need to be measured, a quadrupole mass spectrometer (QMS 200, Pfeiffer Vacuum) (3) is used to determine the concentration.

3. Theory

3.1. Tracer gas method

The high temperatures, high air mass flow, openness and presence of concentrated solar radiation of the future measurement environment pose requirements on the choice of tracer gas. The tracer gas must hence be environmentally friendly, stable under high temperatures and may only occur in air in low concentrations (see Table 1). This reduces the choice of tracer gases down to the noble gases. Due to economic reasons we chose helium.

The relative leak rate of the system per circulation is defined as

Table 1
The table shows different tracer gas candidates and their suitability according to different aspects. H* stands for forming gas, which is a mixture of 95% nitrogen and 5% hydrogen giving the properties of hydrogen gas without being explosive. (++: excellent, +: good, o: fair, -: poor, - -: very poor).

Evaluation criteria	Ar	CO_2	He	H*	SF6	Ne
Natural conc.	− −	− −	+	++	++	++
Pollution	++	o	++	+	− −	++
Therm. stability	++	++	++	− −	− −	++
Price of gas	+	++	−	++	−	− −