COMBINED MEASUREMENT OF THERMAL AND OPTICAL PROPERTIES OF RECEIVERS FOR PARABOLIC TROUGH COLLECTORS

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Abstract

Two new test benches have been developed for the combined measurement of the thermal properties and overall optical efficiencies of receivers for the use in parabolic trough collectors. In the first test bench two receivers are simultaneously irradiated by natural sunlight via parabolic troughs that are mounted on a two axis tracking stage. Shutters enable the variation of the aperture for quasi constant solar input power over the test period. The second, the solar simulator test bench consists of an elliptical cylinder with flat end reflectors. Metal halide lamps (HMI) and the receiver are positioned in the two respective focal lines. The test benches are operated in two modes: Cold performance tests with water flow through the receiver at near ambient temperature in order to measure the optical efficiency in the stationary enthalpy increase, secondly hot testing with the empty receiver at typical operating temperature in order to compare irradiant power and steady state thermal loss power and calculate the efficiency. The test benches are operated in combination with classic heat loss measurement, together the three test benches form a complementary set. First comparative measurements with cold testing on the solar simulator test bench show high reproducibility and a measurement precision relevant for qualification and comparison of different receiver types at industrial and research level.

Keywords: parabolic trough, receiver, thermal loss, optical efficiency, test bench

1. Introduction

The receiver is a key component in parabolic trough power plant collectors. Its performance directly influences the performance of the whole power plant. Therefore the measurement of its performance is essential to evaluate existing designs, to assess production quality, for the comparison and selection of products and to monitor the performance over the time of use of the receivers. The two key figures of a receiver are the

- optical efficiency, quantifying the absorbed power versus the incident solar radiation of the receiver, and the
- thermal loss power at operating temperature.

It is desirable to measure key values of the entire receiver with intact glass envelope and vacuum. Thermal loss measurements of entire receivers have been performed in the past and deliver the specific heat loss power under laboratory conditions. The comparison with field measurements demonstrated that the results are relevant for the field conditions [1]. These measurements however do not include the optical and geometrical properties of the receivers. Two new test benches for the measurement of entire receivers have been developed at DLR using light for heating the receiver. Hence they expand the existing facilities towards measurements of the absorbed light at ambient temperature as well as at typical operating temperatures of 300-500°C.

2. Energy balance of the parabolic trough receiver

The energy balance of the parabolic trough receiver is determined from the absorbed power P_{abs}. That is the incoming intercepted solar radiation P_{in}, attenuated due to optical effects and finally absorbed on the active absorber surface. The description is divided into optical and geometrical effects [2]. Optical effects are those types of attenuation depending on surface and coating, including glass transmittance, absorber absorptance, and dirt on the glass surface. These attenuations, some of which are dependent on the incidence angle, are combined to the *optical efficiency* of the receiver $\eta_{opt,rec}$ with respect to the (net) receiver area. Geometric effects are all effects reducing the available absorber surface due to supports and bellows at the glass-to-metal joint. This is included by introducing the *net area factor* of the receiver ψ_{rec}, being the ratio of the effective area of the absorber at 0° incidence angle and the ideally possible area. Due to thermal expansion the net area factor depends on the temperature of the absorber $\psi_{rec}(T_{abs})$. As there are different bellow designs, this temperature dependence can have a positive or a negative impact on the performance at operating temperature. All geometric effects, that depend on the incidence angle θ, are included via the incidence angle modifier $\kappa_{geo,rec}(\theta)$, which equals 1 at $\theta = 0$ [2]. Hence, the *geometric efficiency* of the receiver is

$$\eta_{geo,rec}(\theta) = \psi_{rec}(T_{abs}) \cdot \kappa_{geo,rec}(\theta) .$$

Gross optical efficiency, or opto-geometric efficiency $\eta_{opt,geo,rec}$ of the receiver is the product of geometric and optical efficiency. This value is the relevant performance parameter for a trough receiver.

$$\eta_{opt,geo,rec} \equiv \eta_{opt,rec} \cdot \eta_{geo,rec} .$$

The absorbed power P_{abs} is the sum of useful collector power P_{coll} increasing the enthalpy of the heat transfer fluid and thermal losses through the glass and over the supports $P_{th,loss}$

$$P_{abs} = P_{in} \cdot \eta_{opt,geo,rec} = P_{th,loss} + P_{coll} .$$

Thermal loss mechanisms include conduction, radiation and convection and depend on environmental conditions.

3. Test benches

3.1. Thermal loss measurement

Laboratory test benches for thermal loss measurements of receivers exist at DLR, NREL and at manufacturer laboratories [1, 3]. At these test benches, the absorber tube is heated with an internal electrical heating. The electrical heating power is measured and is equal to the thermal loss power $P_{th,loss}$ of the receiver, once steady temperature is reached at constant heating power. To prevent heat losses at the ends of the receiver, the ends are either carefully insulated (DLR), or additional heating prevents heat losses (NREL), aiming at adiabatic conditions at both receiver tube ends.

The thermal loss power of the receiver is measured as a function of absorber temperature $P_{th,loss}(T_{abs})$ at typical operating temperatures, e.g. up to 500°C. Environmental factors affecting thermal losses like ambient temperature and wind speed need to be controlled in order to get comparable results. Details of the losses at the receiver mountings have not been analyzed.

3.2 Solar receiver test bench - SolaRec

The objective of the solar receiver test bench (Figure 1) is to include the solar energy input in the energy balance of the thermal tests and hence acquire information about the opto-geometric efficiency $\eta_{opt,geo,rec}$. The test bench consists of two parabolic trough collector modules tracked in two axes to the sun. The chosen trough for testing of receivers of 70-100 mm diameter has an aperture width of 2.3 m, 5 m module length, and 0.80 m of focal length. As the trough is designed for a smaller absorber diameter, a high intercept factor of the system of > 98% is achieved.

Figure 1: SolaRec Solar Receiver Test Bench

Figure 2: ElliRec Elliptical Simulator Receiver Test Bench

Shutter mechanisms enables to partially cover the aperture area and automatically control the incident solar power P_{in} onto the receivers. For this purpose, the beam irradiance is constantly monitored. Two receivers are tested simultaneously for comparative measurements using reference samples. Detailed characterization of the concentrator optical performance is used to determine the incoming solar power on the receiver P_{in}. Two types of tests are performed under these conditions:

1. Cold test: In this test water at ambient temperature runs through the absorber tube keeping the absorber near ambient temperature as well. As thermal losses can be neglected under these conditions ($P_{th,loss} \approx 0$), the measured temperature increase of the water (4-10 K) and the measured flow rate (400-800 L/h) can be used to calculate the absorbed power P_{coll}. The optical efficiency of the receiver at near ambient temperature and $\theta = 0°$ can be determined, as the incident power P_{in} is known from the irradiance measurements, aperture area and concentrator characteristics (see 4.1). A displacer cylinder inside the absorber tube improves the heat transfer from absorber tube to heat transfer fluid, lowers the temperature of the absorber, and hence minimizes heat losses.

2. Hot test: Like for thermal loss measurements (3.1), the absorber tube is heated to steady elevated temperature with constant incoming power. No heat transfer fluid extracts power ($P_{coll} = 0$). There are two ways to evaluate this test: Firstly, if thermal losses $P_{th,loss}(T_{abs})$ are known (3.1), then the optical efficiency at the temperature can be calculated be dividing it by the incoming solar power P_{in}. Secondly, if the optical efficiency is known form a cold test, the thermal losses $P_{th,loss}(T_{abs})$ can be calculated from P_{in}. Such tests with reduced amount of natural sunlight provide reasonable testing conditions, however they are limited by the availability of sunshine.

3.3. Elliptical simulator receiver test bench - ElliRec

In order to be independent from the weather, a solar simulator test bench has been designed (Figure 2, right). Metal halide lamps (HMI) have been identified as best compromise of solar-like spectral properties (Figure 3), small size of the light source and hence high radiant exitance. The test bench is an elliptical mirror cylinder with flat end reflectors surrounding both the receiver in one focal line and the arc lamps in the second focal line. Ray-tracing calculations (OptiCAD®) have been used to identify a design with appropriately homogeneous distribution of radiation over the receiver length. This resulted in ellipse diameters of 1.0 and 0.7 m respectively, and a length of 5.0 m. 6 lamps are installed, 2x 1.2 kW, 2x 2.5 kW and 2x 4 kW. Ray-tracing has shown that the operation of each of the pairs of lamps of equal power results in homogeneous light flux distribution along the receiver (figure 4). Choice of appropriate pairs of lamps allows stepwise power selection. The power input can be varied from 2.4-13 kW. This test bench serves for both cold and hot tests as described in 3.2.

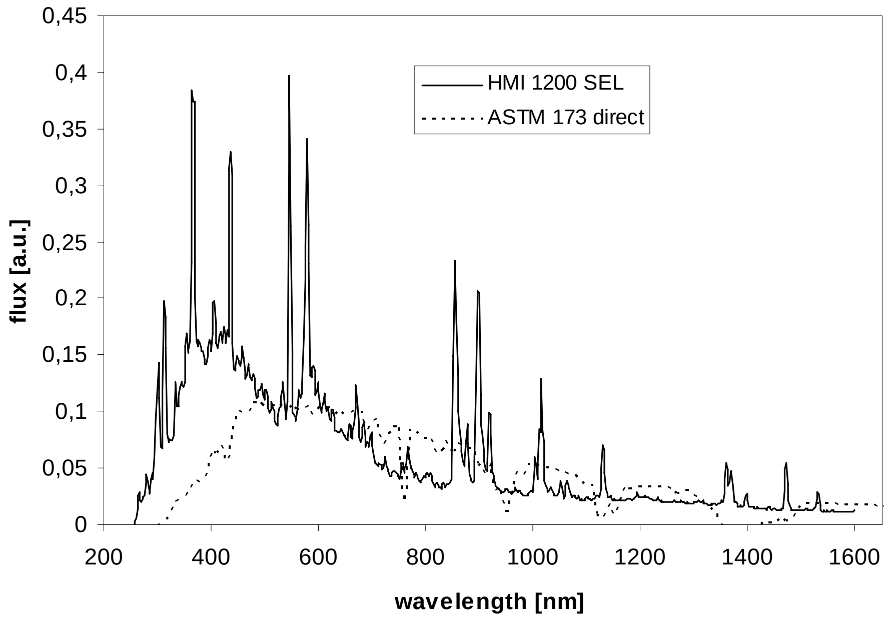

Figure 3: Spectrum of the 1200 W HMI-lamps (source: OSRAM) and ASTM 173 direct

While in the SolaRec the incidence angle is well defined and usually chosen to be $\theta \approx 0°$, the ElliRec provides a mixture of a wide range of incident angles. The impact of the lamp spectrum deviating from the solar spectrum still needs to be characterized. As the SolaRec works with real sunlight, a comparison of the results of these two test benches will indicate the significance of this deviation.

4. First results

4.1. Characterisation of the SolaRec

The optical performance characteristics of the two parabolic trough collectors have been determined. Using the absorber reflection method described in [4] the intercept factors of the two troughs were measured to be 0.981 and 0.985 respectively. Figure 5 shows the detailed maps of the slope deviation of both modules. The solar weighted direct reflectivity at 25 mrad full acceptance angle was measured to be $\rho_{SWD} = 0.79$.

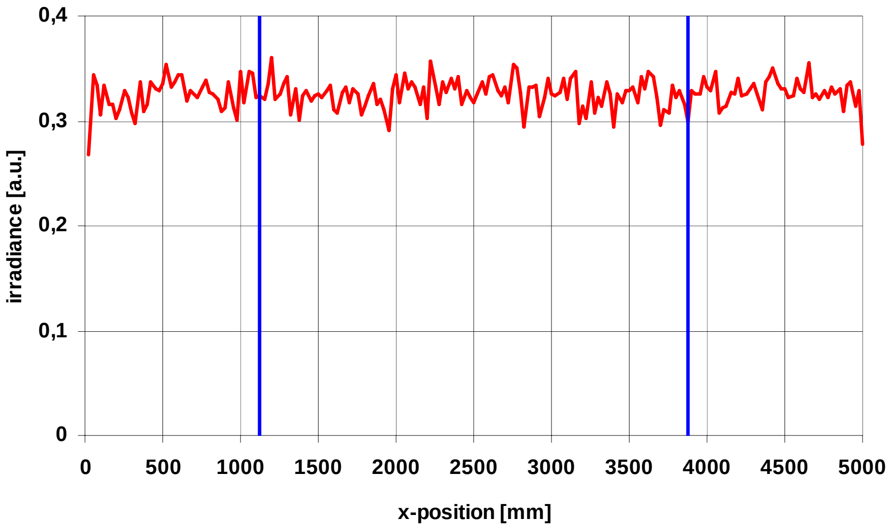

Figure 4: Ray-tracing calculation of irradiance distribution of the ElliRec at the focal line, the vertical lines indicate the positions of the two lamps in operation

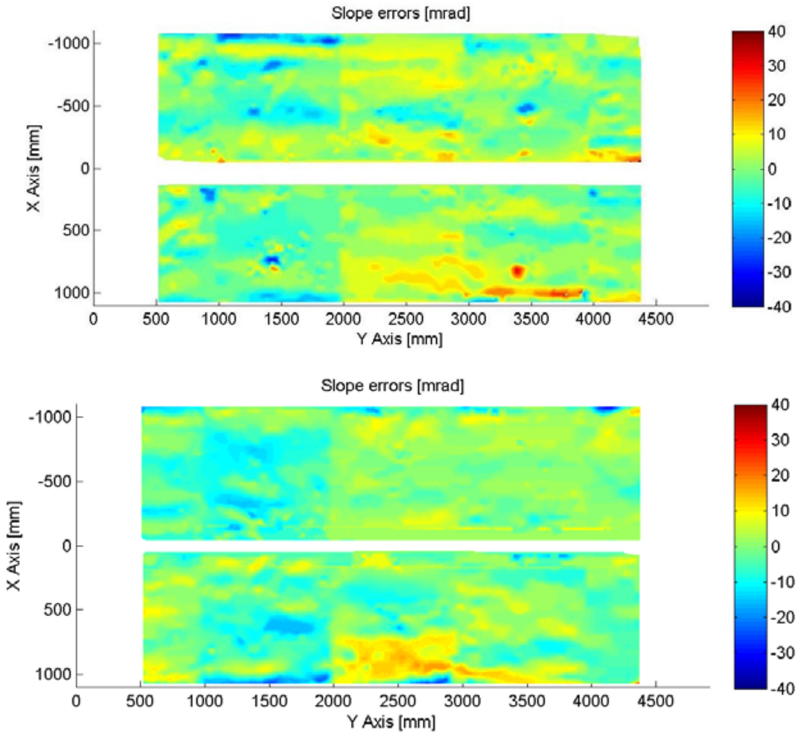

Figure 5: Slope deviation maps of the two parabolic trough modules of the SolaRec

	Description
receiver 1	manufacturer 1, older generation receiver
receiver 2	manufacturer 2, prototype receiver, no AR-coating
receiver 3	manufacturer 3, state of the art receiver

Table 1: List of tested receivers

4.2. Elliptical receiver test bench test result

The optical quality of the elliptical receiver test bench has not been evaluated in detail until now. However based on the reproducibility of the testing, comparative measurements have been performed using the cold test method (3.2). Three different parabolic trough vacuum receivers (Table 1) with similar geometric properties, length (4060 mm) and absorber diameter (70 mm) have been subject to the test.

Results of the measurements with a connection power of 10.4 kW are shown in Figure 6.

5. Discussion

The results of the solar simulator receiver test bench show the method to be repeatable and precise enough to be useful for the evaluation of the optical efficiency of single receivers. As the tested receivers have identical basic geometries, the absorbed powers shown in figure 6 are proportional to the opto-geometric efficiencies at ambient temperatures.

Furthermore, the repeatability of the measurement after demounting the receiver is an indication that the adjustment of the receiver and the lamps work reasonably well. The measured absorbed power shows the mean flux density at the absorber position to be at least 4.5 kW m^{-2}.

However, a detailed characterisation of the flux densities at the absorber position as well as the implementation of a monitoring system for the lamp performance and spectra have yet to be performed at the ElliRec test bench.

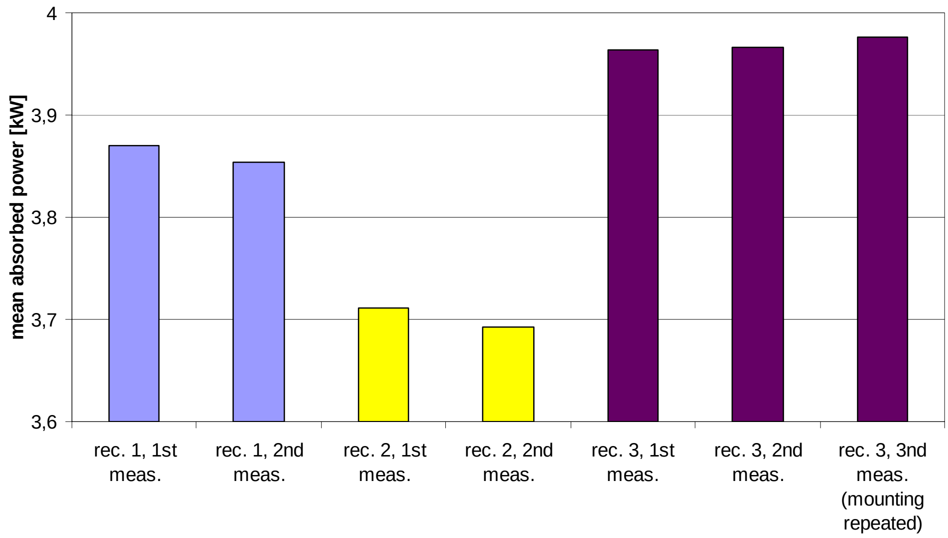

Figure 6: Comparative measurements with ElliRec of three different receivers, configuration 2x 4 kW and 2x 1.2 kW

6. Conclusion

Two new test setups have been finished for testing receiver performance independently from a solar field installation. One is working with natural sunlight, the other uses simulated sunlight. In addition to classic heat loss measurements, the tests form a complementary set of test benches which provide the possibility to measure the overall optical efficiency of single receivers.

Results of the simulator receiver test bench working with HMI lamps are promising as they show good repeatability of the measurement. The simulator test bench provides for the first time reproducible test conditions in a linear focus of concentrated sunlight.

Comparison between the various test methods and evaluation is ongoing.

Acknowledgements

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