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Parabolic Trough Receiver Heat Loss and Optical Efficiency Round Robin 2015/2016

Johannes Pernpeintner[1, a)] and Björn Schiricke[1], Fabienne Sallaberry[2], Alberto García de Jalón[2], Rafael López-Martín[3], Loreto Valenzuela[3], Antonio de Luca[4], Andreas Georg[5]

[1]*German Aerospace Center DLR, Linder Hoehe, 50677 Koeln, Germany*
[2]*CENER (National Renewables Energy Center), C/ Ciudad de la Innovación, 7-31621, Spain*
[3]*CIEMAT – Plataforma Solar de Almería, Crta. Senés, km4.5, E04200 Tabernas, Almería, Spain*
[4]*ENEA R.C. Casaccia, Via Anguillarese 301,00123 S. M. di Galeria, Rome, Italy*
[5]*Fraunhofer Institute for Solar Energy Systems, Heidenhoferstr. 2, 79110 Freiburg, Germany*

[a)]Corresponding author: Johannes.Pernpeintner@dlr.de

Abstract. A round robin for parabolic trough receiver heat loss and optical efficiency in the laboratory was performed between five institutions using five receivers in 2015/2016. Heat loss testing was performed at three cartridge heater test benches and one Joule heating test bench in the temperature range between 100 °C and 550 °C. Optical efficiency testing was performed with two spectrometric test bench and one calorimetric test bench. Heat loss testing results showed standard deviations at the order of 6% to 12 % for most temperatures and receivers and a standard deviation of 17 % for one receiver at 100 °C. Optical efficiency is presented normalized for laboratories showing standard deviations of 0.3 % to 1.3 % depending on the receiver.

INTRODUCTION

In a concentrating solar power plant the efficiency of the receiver is of major importance to the overall efficiency of the plant. Hence, test benches for the measurement of heat loss and optical efficiency of parabolic trough receivers have been built at several research institutions. While outdoor test benches [13-15] and indoor test benches [1- 8] have been developed for testing of parabolic trough receivers, primarily indoor test benches are in use. The main parameters under investigation in these test benches are heat loss [1-4, 8] and optical efficiency [4-8]. A first round robin campaign in 2010 [1] compared the heat loss measurements of three receivers at NREL, DLR, and SCHOTT Solar. The conditions for the round robin were not optimal and the comparison of all institutions could be made for 400 °C only. Additionally, SCHOTT Solar measured a different set of receivers from the same production batch, assuming the stability of production was adequate for a comparison. The results showed deviations of < 10 % between the institutions with no particular deviation of the measurement by SCHOTT Solar.

This paper describes a round robin performed in 2015 and 2016 with the participation of ENEA, CENER, DLR, CIEMAT-PSA and Fraunhofer ISE. Heat loss measurements were to be performed at target temperatures of [250, 300, 400, 500, 550] °C for receivers for usage with solar salt, and at [100, 200, 300, 400, 450] °C for receiver for usage with thermal oil. Additionally, optical efficiency was measured in spite of differences in measurement approaches and hence a difficulty to compare results.

SCHOTT Solar provided two receivers, Archimede Solar Energy (ASE) provided three receivers for this exercise. Out of the five receivers, one is for operation with thermal oil, four are for operation with solar salt. Receiver length is $l_{rec} = 4.07\,\mathrm{m}$ at room temperature, absorber outside diameter is 70 mm. Absorber tube thickness is 2 mm for the receivers from SCHOTT Solar and 3 mm for the receivers from ASE.

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The receivers are sent to DLR, CENER, ENEA, CIEMAT-PSA, Fraunhofer ISE, and back to DLR for a second measurement for the verification of sample stability about 1 year and two months later. For the round robin the result of the first measurement is used. Heat loss testing is performed by CENER, DLR, ENEA, and CIEMAT-PSA. Optical efficiency testing is performed by DLR, CENER, and Fraunhofer ISE. The results are presented anonymized both with regards to the receivers and laboratories.

TESTING PROCEDURES

Heat Loss Testing

Heat loss testing in the laboratory is accomplished by heating the receiver electrically to a steady state at operating temperature. DLR and CENER utilize long electrical cartridge heaters inserted into the absorber [1-4, 6, 8], where heat is transferred from heater to the absorber by radiation and convection. At CIEMAT-PSA also long cartridge heaters are used, however, the test is performed under vacuum with heat transfer from heater to absorber by radiation. At the test bench of ENEA electrodes are connected to the ends of the absorber directing an electrical current through the stainless steel absorber (Joule-type). Temperature measurement for all test benches is performed with multiple thermocouples pressed on the inner surface of the absorber. Typically the average of the measured temperatures of the inner surface of the absorber gives the receiver temperature. DLR corrects the systematic error of the temperature measurement due to the influence of the radiation temperature and air temperature in the annulus on the thermocouples and temperature drop via the steel tube yielding the temperature of the outer surface of the absorber. As this and other corrections are performed subsequent to the measurement, the result is a pair of heat loss power HL in W and a mean temperature of the absorber (inside or outside surface) near the target temperatures. Length specific heat loss power $hl = HL / l_{rec}$ in $\mathrm{W/m}$, is calculated using the cold receiver length l_{rec} due to the difficulty to measure receiver length at elevated temperature.

Optical Efficiency Testing

Optical efficiency $\eta_{opt,rec}$ of a receiver can be expressed by the product of the net area factor ψ_{net} and the solar weighted transmittance-absorptance product $(\tau\alpha)$ by

$$\eta_{opt,rec} \approx (\tau\alpha) \cdot \psi_{net} . \tag{1}$$

The net area factor ψ_{net} describes the geometrical efficiency of the receiver due to loss by shading of the focal line at the bellows. For perpendicular irradiation the net area factor $\psi_{net} = l_{aperture} / l_{rec}$ is the fraction of receiver aperture $l_{aperture}$ and receiver length l_{rec}. The solar weighted transmittance-absorptance product $(\tau\alpha)$ is dependent on the transmittance of the glass envelope τ as function of the wavelength λ, also called spectral transmittance $\tau(\lambda)$, dependent on the spectral absorptance $\alpha(\lambda)$ of the absorber, and dependent on the spectral irradiance distribution in $E_\lambda(\lambda)$ of the radiation incident on the receiver, which is the power per area and wavelength interval with unit $\mathrm{W/(m^2 \cdot nm)}$ by

$$(\tau\alpha) = \frac{\int \tau(\lambda) \cdot \alpha(\lambda) \cdot E_\lambda(\lambda) d\lambda}{\int E_\lambda(\lambda) d\lambda} . \tag{2}$$

CENER and Fraunhofer ISE performed spectrophotometric measurements of spectral transmittance $\tau(\lambda)$ and spectral absorptance $\alpha(\lambda)$, DLR performed a calorimetric measurement of optical efficiency $\eta_{opt,rec}$.

In the method of Fraunhofer ISE a set of halogen lamps together with an integrating cylinder surrounding the receiver are used to illuminate the receiver hemispherically. The setup also consists of a directional viewing optics connected to a spectrophotometer, a movable reference sample and a movable blind. Two measurements are taken: First, by blocking the reflection at the absorber tube with the blind, the spectral reflectance of the glass envelope $\rho_g(\lambda)$ is measured. By neglecting absorption in the glass, the conservation of energy $\tau(\lambda) = 1 - \rho_g(\lambda)$ is used to calculate transmittance of the glass envelope $\tau(\lambda)$. Second, reflectance of the absorber $\rho_a(\lambda)$ is measured through the glass yielding $\tau^2(\lambda)\rho_a(\lambda)$. Hence, by neglecting transmittance through the absorber, the conservation of energy $\alpha(\lambda)=1-\rho_a(\lambda)$ can be used to calculate absorptance of the absorber $\alpha(\lambda)$. The spectrophotometric measurement at CENER is described in [4, 7]. A first measurement channel allows for the measurement of the square of transmittance of the glass $\tau^2(\lambda)$ by shining light through the receiver beside the absorber. A second measurement channel allows for the measurement of reflectance of the absorber as viewed through the glass $\tau^2(\lambda)\rho_a(\lambda)$. Neglecting transmittance through the absorber, the conservation of energy $\alpha(\lambda)=1-\rho_a(\lambda)$ can be used to calculate absorptance of the absorber $\alpha(\lambda)$. The solar weighted transmittance-absorptance product $(\tau\alpha)$ is calculated from spectral absorptance $\alpha(\lambda)$ and spectral transmittance $\tau(\lambda)$ using Eq. 2 and the standard ASTM G173-03 [10] direct solar spectrum.

DLR uses a linear focus solar simulator test bench described in [6, 8] to assess the optical efficiency of parabolic trough receivers. The sample receiver is positioned in the focal line of a solar simulator based on metal halide lamps. By comparing the enthalpy increase of water running through the receiver and a reference receiver DLR70-1 the measurement result is the optical efficiency $\eta_{opt,rec}(sample, RT)$ expressed relative to the optical efficiency of the reference receiver DLR70-1 $\eta_{opt,rec}(DLR70-1, RT)$ at room temperature RT.

EVALUATION OF ROUND ROBIN

Heat Loss Testing

For the comparison of heat loss results the temperature of the receiver T is chosen to be the outside absorber surface temperature T_o. It is calculated for given inner surface temperature T_i by [10]

$$hl = \lambda \cdot S_1 \cdot (T_i - T_o), \qquad \text{with } S_1 = \frac{2\pi}{\ln(r_o / r_i)}, \tag{3}$$

and the outside absorber radius $r_o = 35\text{mm}$, inside absorber radius $r_i = 32\text{mm}$ (ASE) or $r_i = 33\text{mm}$ (SCHOTT Solar). Assuming a thermal conductivity for stainless steel of $\lambda = 17\text{W/(m}\cdot\text{K)}$ [11] the temperature difference $(T_i - T_o)$ is at the order of 0.1 K to 0.7 K. Temperature uncertainties $u(T)$ are assumed to be identical for inner and outer surface. In a second step the measurement is interpolated and extrapolated to the target temperature using a piecewise cubic hermite spline interpolation. The measurement is discarded, if extrapolation is > 10 K. Spline interpolation, in contrast to using the model fit-function $hl = a \cdot T_{abs}^4 + b \cdot T_{abs}$ from [1], has the advantage that experimental data exactly lays on the interpolation curve.

Uncertainty u of the measurement is given by some laboratories independently for heat loss $u(hl)$ and temperature $u(T)$. Hence a combined uncertainty of heat loss $u_c(hl)$ is calculated by

$$u_c^2(hl) = u^2(hl) + \left(\frac{\partial}{\partial T} hl(T)\right)^2 \cdot u^2(T). \tag{4}$$

The uncertainty of the temperature $u(T)$ is interpolated using a piecewise cubic hermite interpolation to the target temperature. The partial derivative $\partial / \partial T(hl(T))$ is determined numerically from the interpolation curve.

Anonymized heat loss hl_{norm} is calculated from heat loss hl (including corrections and interpolations) by normalization to the mean of all measurements of the identical receiver at identical target temperature $hl_{\bar{j}}$ by

$$hl_{norm} = \frac{hl}{hl_{\bar{j}}}, \qquad \text{with } hl_{\bar{j}} = \frac{1}{n_j}\sum_{j=1}^{n_j} hl_j, \tag{5}$$

where hl_j are the measurements of all laboratories of the identical receiver at identical temperature and n_j is the number of measurements of all laboratories of the identical receiver.

Optical Efficiency Testing

For a comparison of measurement results the optical efficiency $\eta_{opt,rec}$ is chosen. Hence, for given $(\tau\alpha)$ Eq. 1 is applied with the assumption of perpendicular irradiance $\psi_{net} = l_{aperture} / l_{rec}$ using measured aperture lengths $l_{aperture}$. As DLR measures optical efficiency $\eta_{opt,rec}$ relative to a reference receiver, the optical efficiencies $\eta_{opt,rec}$ are subsequently normalized to the mean of all receivers $\eta_{opt,rec,\bar{i}}$ measured by the laboratory

$$\eta_{opt,rec,norm1} = \frac{\eta_{opt,rec}}{\eta_{opt,rec,\bar{i}}}, \qquad \text{with } \eta_{opt,rec,\bar{i}} = \frac{1}{n_i}\sum_{i=1}^{n_i}\eta_{opt,rec,i}, \tag{6}$$

where $\eta_{opt,rec,norm1}$ is the laboratory-normalized optical efficiency, $\eta_{opt,rec,i}$ are the measurements of all receivers of the identical laboratory and n_i is the number of measurements of all receivers of the identical laboratory. For annonymization of receiver performance, all laboratory-normalized optical efficiency results $\eta_{opt,rec,norm1}$ are normalized again to the mean of the measurements of all laboratories of the identical receiver $\eta_{opt,rec,norm1,\bar{j}}$ by

$$\eta_{opt,rec,norm2} = \frac{\eta_{opt,rec,norm1}}{\eta_{opt,rec,norm1,\bar{j}}}, \qquad \text{with } \eta_{opt,rec,norm1,\bar{j}} = \frac{1}{n_j}\sum_{j=1}^{n_j}\eta_{opt,rec,norm1,j}, \tag{7}$$

where $\eta_{opt,rec,norm2}$ is the (doubly) normalized optical efficiency, $\eta_{opt,rec,norm1,j}$ are the measurements of all laboratories of the identical receiver, and n_j is the number of measurements of all laboratories of the identical receiver.

What core information is left in the quantity $\eta_{opt,rec,norm2}$? The first normalization preserves the relative differences between receivers as they are measured by one laboratory by cutting the relative difference between laboratories. The second normalization merely anonymizes the actual performance of the receiver. Hence, if all resulting normalized optical efficiencies $\eta_{opt,rec,norm2}$ are close to 1, then all laboratories do measure a similar relative performance and all laboratories can differentiate between high and low performing receivers. However, it does not state something about the question, if the measurement at one laboratory can be compared to the measurement at another laboratory. However, for the heat loss normalization according to Eq. 5 this information is preserved.

Comparison

The comparison of the result of the laboratories is presented as graphs of normalized measurement results, expanded uncertainty error bars (k=2 for 95% of coverage), and the standard deviation std. For heat loss the Z_{score} is determined. Standard deviation $std(x)$ in this paper is the corrected standard deviation of the measurements x_j of all laboratories j defined as

$$std(x) = \frac{1}{n_j - 1}\sum_{j=1}^{n_j}(x_j - \bar{x})^2, \qquad \text{with } \bar{x} = \frac{1}{n_j}\sum_{j=1}^{n_j}x_j, \tag{8}$$

where $\bar{x}$ is the arithmetic mean of the measurements of all laboratories and n_j is the number of laboratories. The Z_{score} (ISO 13528 [13]) of a measurement of a laboratory is calculated according to

$$Z_{score} = \frac{x - \bar{x}}{std(x)} \tag{9}$$

The measurement is considered acceptable for $|Z_{score}| \le 2$, questionable for $2 < |Z_{score}| \le 3$, and not acceptable for $3 < |Z_{score}|$.

RESULTS AND DISCUSSION

Fig. 1a shows the normalized heat loss at several temperatures. One of the laboratories provided steady-state stability of the measurement instead of measurement uncertainty leading to a very small error bar. Measurements at 550 °C were performed by three laboratories. Heat loss measurements deviate more than stated uncertainties indicating that uncertainties are too optimistic by some or all laboratories. Standard deviation is typically between 6% to 12 % and does not show an obvious dependence on temperature. The measurement at 100 °C shows the largest standard deviation with 18% showing the difficulty of measurements at low temperatures, where heat loss of these receivers is very low. All measurements are at $Z_{score} < 2$ and hence fall within the 'acceptable' category (Fig. 1b).

With the exception of receiver R2 the normalized optical efficiencies (Fig 2.a) agree within the error bars. Standard deviation of normalized optical efficiency of receivers R1, R3, R4, and R5 is between 0.2 % and 0.6 %. For receiver R2 the standard deviation is very high with 1.3 %. As explained above, normalized optical efficiency (as used in this paper) only indicates the ability of the laboratory to recognize a well performing receiver relative to the measurements at the same laboratory.

Relative change in measured heat loss is shown in Fig. 2b, and relative change in optical efficiency in Fig. 2c. The changes were determined by one measurement each. All heat loss measurements have increased throughout the campaign. For receivers R1, R2, R3, and R4 the measured heat loss shown in Fig. 2b has increased by 5 % to 10 % with no general temperature dependence. For receiver R5 measured heat loss has increased by 28 % to 10 %. For this receiver the change in heat loss decreases with increasing temperature. Due to the increase of measured heat loss for all receivers, the question on test bench stability arises. DLR performs regular measurements of a reference receiver, which was also measured at the time of the first the last measurement for the round robin. There was an increase in measured heat loss by 2 % (250 °C), 3 % (300 °C), 2 % (350 °C) and 1 % (400 °C) and hence smaller the increase in the round robin. Long term observations of this reference receiver show a 2σ-reproducibility of ±4.9 % (250 °C), ±4.7 % (300 °C), ±2.4 % (350 °C), and ±1.7 % (400 °C). This reproducibility is included in the uncertainty calculation, as constant value of 2 % (2σ) in the tool used to calculate uncertainties of the round robin. However, the measured changes in heat loss in the round robin are twice as large as the observed change in test bench. Hence it cannot be ruled out, that the receivers have changed their properties during the campaign.

The measured optical efficiency of the receivers, shown in Fig. 2.c, also indicates a change in optical performance. Error bars in Fig. 2.c show 2σ-reproducibilty, as a full uncertainty evaluation is not available. The change might be attributable to wear of the AR-coating during the campaign and stains visible on the receiver envelopes after the campaign. However, again the question of stability of the test bench arises. As the optical efficiency measurement is performed relative to reference receiver, wear of the simulator optics can be ruled out. As the spectrum of the lamps is not monitored, a spectral shift in the illumination light could be a contributing factor, but deemed unlikely. A decrease in optical efficiency of the reference receiver would result in an increase of measured optical performance, the opposite to the observed effect. In conclusion a change to lower measured optical efficiency due to change in the test bench at the observed magnitude seems unlikely and should be, at least partially, attributable to the receivers.

CONCLUSION

A round robin for performance testing of parabolic trough receivers in the laboratory has been performed in collaboration of five laboratories and two receiver manufacturers. Heat loss tests, with four laboratories participating and were performed at temperatures between 100 °C and 550 °C and showed standard deviations of typically 6 % to 12 % and 18 % at 100°C. Three laboratories participated in optical efficiency testing. Due to different methodologies, only a normalized comparison was possible, where an absolute comparison between the laboratories is lost. This comparison revealed standard deviations of 0.2 % to 0.6 % and one receiver with 1.3 %.

The evaluation of sample stability measurements performed before and after the campaign, revealed a drift in measured parameters. Heat loss increased 5% to 10% for most receivers, for one receiver increased for 28 %. Measured optical efficiency decreased by 0.2% to 0.7%. These changes might partly be attributable to reproducibility or drift of the test benches, nevertheless stability of the receivers is called into question.

Various corrections had to be performed by the coordinator due to different methodologies in heat loss and optical efficiency testing, in order to enable a meaningful comparison. This underlines the necessity for standards in parabolic trough receiver testing. The evaluation of the heat loss round robin revealed deviations between the laboratories larger than the stated uncertainties. This shows the necessity for reevaluation of the testing procedures at the laboratories. For heat loss measurements deviations appeared to be systematic between the laboratories. Hence caution must be taken, if measurements from different laboratories are compared. The optical efficiency round robin also revealed the lack of standardization in this area. Due to the two different systems in use, optical efficiency and tau-alpha-product, the results could not be compared directly. The results seem promising with standard deviations of normalized optical efficiency of 0.2 % to 0.6 % for four receivers. However, the high degree of abstraction in the evaluation, necessary due to the two systems in use, took away from the information value of the optical efficiency round robin.

The results of the experiences of the round robin will contribute to the standardization process within the standardization committees of AENOR CT 206/SC117 and IEC TC 117 (working group IEC 62862-3-3) and SolarPACES Task III.

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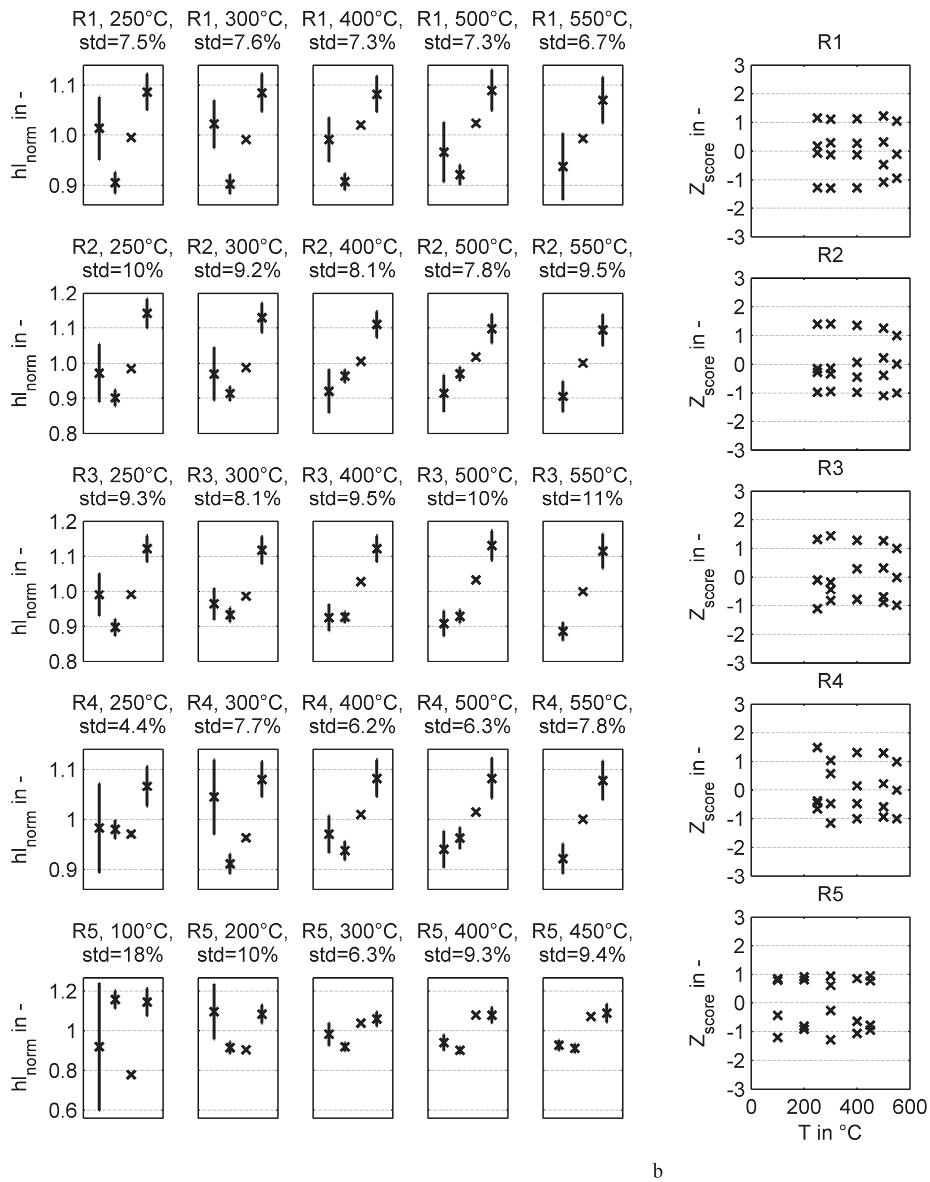

FIGURE 1. a Heat loss normalized for the receiver hl_{norm} for receiver R1 to R5 at various absorber temperatures; *std* is standard deviation of all laboratories for identical receiver and temperature; **b** Z_{score} of heat loss measurements for receivers R1 to R5;

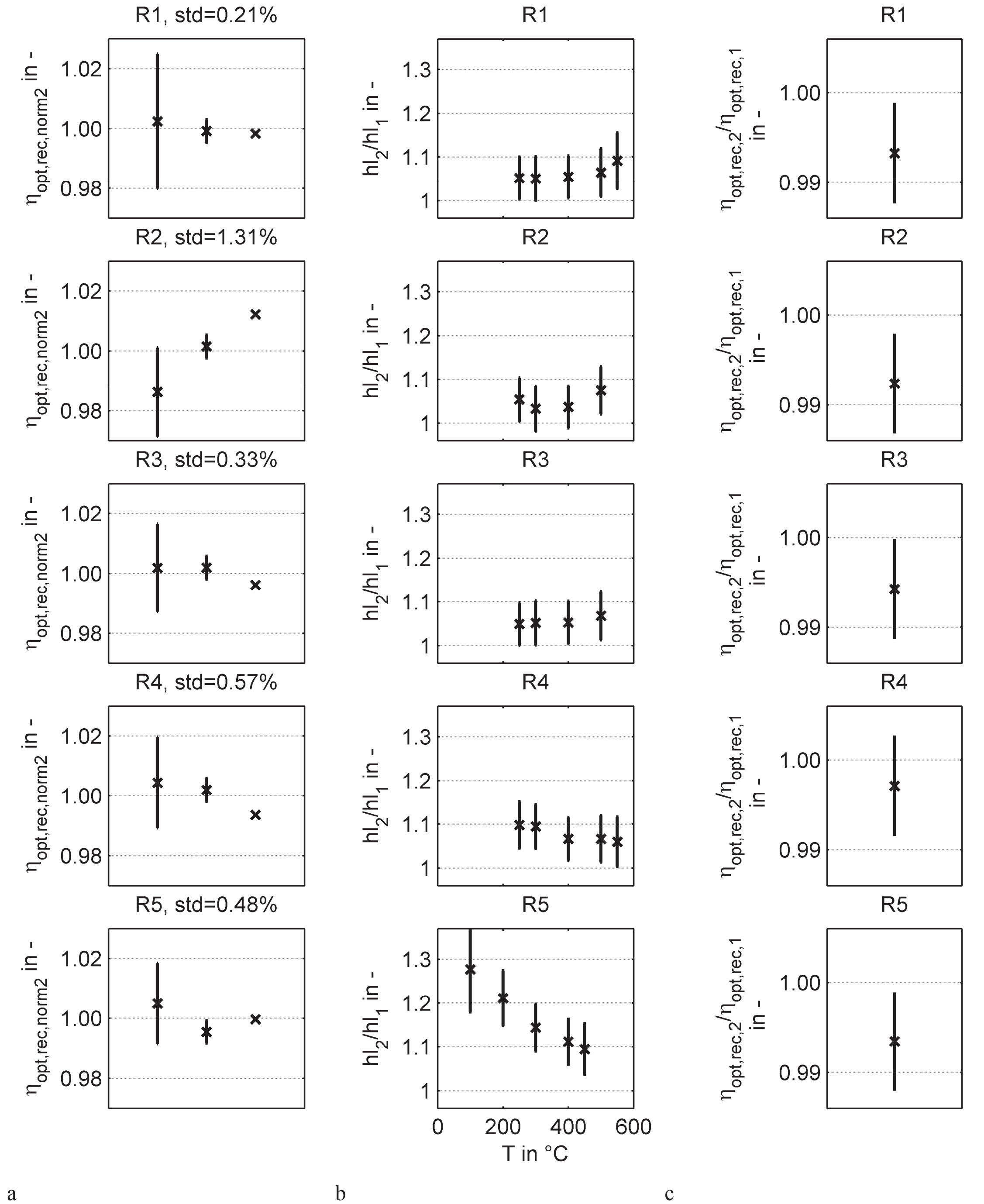

FIGURE 2. a Optical efficiency normalized for laboratory and receiver; *std* is standard deviation of all measurements **b** Stability of heat loss of receiver samples: Comparison of first and second measurement at the beginning and at the end of the round robin; **c.** Stability of optical efficiency of receiver samples: Comparison of first and second measurement at the beginning and at the end of the round robin;

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