HEAT LOSS MEASUREMENTS ON PARABOLIC TROUGH RECEIVERS

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Abstract

A measurement set-up to determine the heat losses of single parabolic trough receiver components at steady state conditions has been developed at Schott. This paper describes the functionality of the set-up and a comparative campaign with three Schott receivers of 7.0, 8.9 and 11.1% emittance (400°C) including test stands at German Aerospace Center (DLR) and U.S. National Renewable Energy Laboratory (NREL). This campaign showed generally good agreement with deviations <10%.

Additionally, results are compared to heat loss predictions derived from optical measurements of the absorber coating via a one-dimensional simulation. The general trend suggests good accordance with a systematical deviation at lower emissivities.

Overall, this non destructive measurement technique provides a good possibility to determine an important receiver specification, its heat loss.

Keywords: Receiver, Heat Loss, Standardization, Parabolic trough

1. Introduction

Parabolic Trough technology needs to establish standardized methods for the qualification of the Solar Field, the Collector System and its components.

For the receiver and the measurement of its heat losses at operating temperatures, laboratory test stands have been built at several institutions like Schott, NREL and DLR. In order to gain confidence in the test stands and the measurement principle a first comparative campaign was initiated by Schott, joined by NREL and DLR.

2. Measurement technique

2.1. General principle

The measuring principle of all three devices (Schott, DLR and NREL) is based on the assumption, that heat loss power equals the input heating power needed to hold the absorber at a temperature level in steady state conditions. Determining the required power input at different temperature levels results in a characteristic heat loss curve of the tested receiver sample.

Above mentioned assumption requires either adiabatic conditions at the ends of the absorber tube or a correction of the results as performed at DLR.

All test stands are laboratory devices and operated indoors. Although using the same principle, the test stands differ in detail.

2.2. Measurement set-up at Schott

The specific heat loss test stand at Schott uses the absorber tube as a resistance heating to reach the fixed temperature levels, which minimizes the setup effort before the measurement.

To determine the absorber temperature, the elongation of the absorber tube is measured and, with the known coefficient of thermal elongation for the respective steel type, translated into the average temperature of the tube.

Using the absorber tube as heater and given a homogeneity of the steel tube, an even temperature distribution over the cross section of the tube is expected. Therefore the temperature of the outer surface of the absorber tube can be seen as the defined temperature for the heat loss, whereas the other devices (DLR, NREL) generate the inner surface of the absorber tube as the defined temperature. Simulations have shown that the temperature difference between the inner and the outer surface of the absorber tube is <1K and therefore well within uncertainties of the measurements. Thus results from DLR, NREL and Schott can be compared directly.

2.3. Measurement set-up at DLR

Thermal loss testing at DLR is performed with one long electrical IR-heating element enclosed by a copper tube and inserted in the absorber tube. At the ends of the receiver, insulated end caps minimise axial heat loss to ~4 % of the heating power. This set-up leads to a distinct axial temperature profile at the absorber with 15-40 K lower temperatures at the ends. The temperatures of the absorber and the copper tube are measured with 15 internal type N thermocouples, the temperatures of the surfaces of glass envelope and end insulation and the ambient temperature are measured with 13 type K thermocouples.

Axial end losses are calculated using the surface temperature of the insulation. The insulated surface above the bellows is not included as these end losses are part of the receivers' heat loss. The correction for axial end losses is calculated taking into account radiation and free convection. Due to the temperature profile a mean temperature T_m of the absorber has to be defined using the individually measured absolute temperatures T_i and corresponding absorber areas A_i in their vicinity via the equation $A_{abs} \cdot (T_m^4 - T_{glass}^4) = Sum(A_i \cdot (T_i^4 - T_{glass}^4))$, where $A_{abs} = Sum(A_i)$ is the total absorber area and T_{glass} the mean temperature of the glass assuming radiation being the dominant loss mechanism.

2.4 Measurement set-up at NREL

The test stand at NREL uses electric resistance heaters on the inside of a receiver to bring the absorber surface up to desired test temperatures. The resistance heaters are surrounded by a copper tube to even out possible axial temperature gradients. The resistance heaters comprise of two cartridge heaters along the whole length of the receiver and four coil heaters, two at each end of the receiver respectively. The two coil heaters at each receiver end are mounted, so that one heater ends up just inside and one just outside of the receiver. The inner coil heater compensates for end loss effects, while the outer coil heater creates a zero temperature gradient on the copper pipe between the coil heaters. The cartridge heater supplies most of the thermal energy to the system, especially at increasing absorber temperatures. Temperatures are measured via ten thermocouples equally spaced along the absorbers length. The stated uncertainty of the NREL test bench is ±5 W/m.

3. Round robin test

3.1. Concept

Several uncertainties to a reliable comparison, such as possible drifts in the receivers' performance, possible drifts in the measurement devices and the measurement influencing the receivers' characteristics, had to be accounted for. Therefore six receivers were specifically manufactured, three working standards with different coating properties and three master standards with similar properties to the working standards, respectively.

In the paper at hand, the measured receivers are differentiated using their different coating properties, e.g. e_{400} = 7.0%, meaning the optical measured emittance of the respective receiver is 0.070 at 400°C. The optical measurement method is explained in Chapter 4.1. The three working standards have emittances of 7.0, 8.9 and 11.1% and the master standards 7.0, 9.3 and 11.4%.

The master standards were stored under stable ambient conditions at Schott. The other three receivers have been sent to the two contributory institutes before returning to Schott. Results from repeatability measurements at Schott suggest no drifts in the receivers' performance influenced by the measurement itself. Possible drifts due to the transport of the receivers are not expected, but will be tested with the second measurement at Schott.

To further ensure comparability, various test conditions were set. Given usual solar field operating temperatures, measurement points between 100°C and 450°C are most interesting. Ambient conditions affect the heat loss in different scales. Simulations have shown that ambient temperature and wind speed within the center area of the receiver affect the heat loss marginally. At the receiver ends on the other hand, wind speed has a relevant influence on the heat loss. Therefore, tests were done with insulation at the receiver ends, similar to the typical shield configurations in solar fields. Because of the selective absorber coating and its high solar absorption, direct solar irradiation results in significant errors in the measurement and had to be avoided.

3.2 Results and discussion

Results in this chapter are generally displayed as heat loss over absolute absorber temperature and ambient temperature given supplemental in the results tables. Regarding the minor influences of the ambient temperature on the heat loss, assuming end insulation, and the ratio ambient fluctuations to absorber temperature being relatively greater, this results in a smaller interpretation error than the display of heat loss over relative absorber temperature. Furthermore, tables show the directly measured heat loss values whereas figures show fitted curves of the results, the fitting curve being $Heatloss = a \cdot T^4_{absorber} + b \cdot T_{absorber}$, thus providing simple correlations for radiation mechanisms in the central area of the receiver and radiation, convection and conduction mechanisms at the ends. Despite theoretical concerns about the fitting curve, fits match very well with the measurement points.

Due to a tight time schedule, NREL could only provide one or two temperature levels, respectively. With a stated uncertainty of $^+/$-5 W/m in the NREL measurements this should be sufficient for a first evaluation.

Heat loss results are given including the receiver end losses (mainly at the bellows). Since end losses are influenced by different insulations, similar insulation was used. The relative error in end loss should therefore be low but has to be further studied in future comparative tests. Receiver end losses at Schott's test stand are presently not yet quantified. Since the configuration of the test stand at the receiver ends generates similar ambient and wall temperatures to the temperatures of the receiver, end losses are possibly smaller than at the other test stands. NRELs end loss determination (see 2.4.) shows that end losses usually are about 10 W/m at 400°C absorber temperature.

The first measurements compared were performed with a receiver with an emittance of about 7% at 400°C. Results displayed in Fig. 1 and Table 1 show very good agreement between the different test stands.

Table 1 Heat losses of the receiver e_{400} = 7.0% at 400°C

Receiver e_{400} = 7.0%	**Absorber temp. (°C)**	**Ambient temp. (°C)**	**Heat loss (W/m)**
DLR	401	22	189
NREL	400	25	198
Schott (e_{400} = 7.0%)	400	28	189

The respective measurement at Schott showed several irregularities, therefore the measurement of the stored receiver with similar optical properties is presented. Both receivers were measured to have an emittance of 7,0% at 400°C, hence heat loss results can directly be compared.

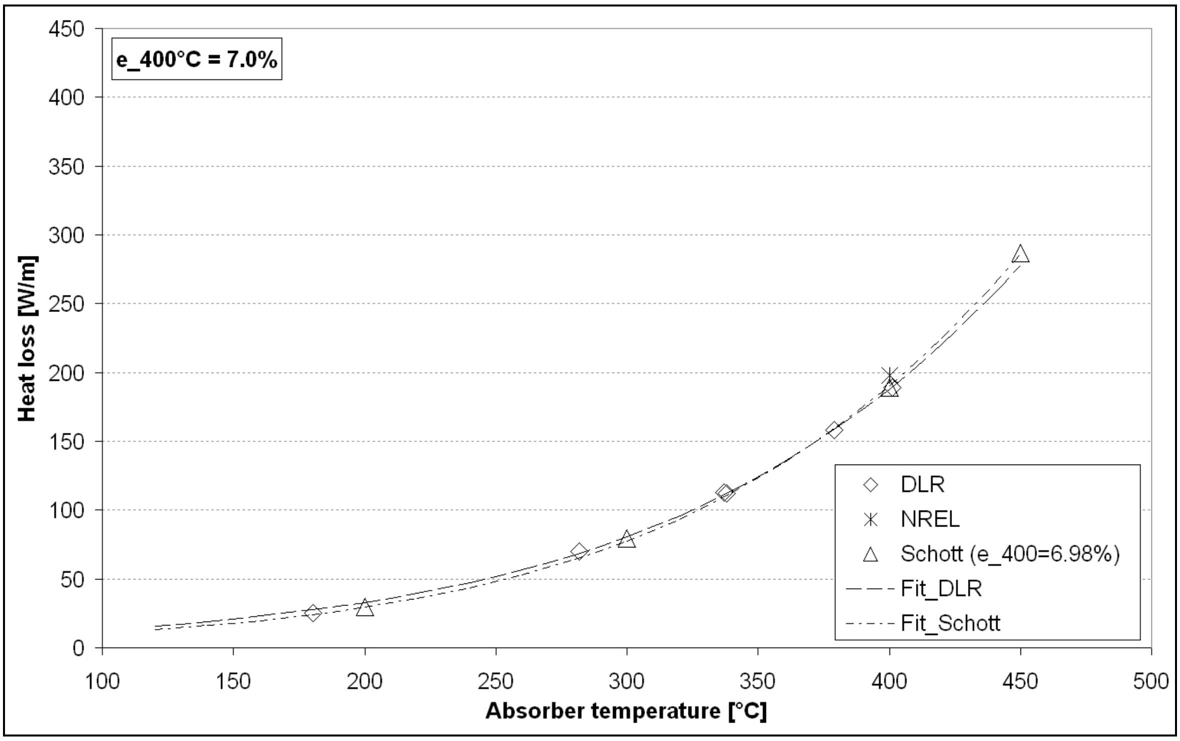

Fig. 1 Heat loss measurement, e_{400} = 7.0%

The second measurement was performed with a receiver with an emittance of 8.9%. Again, results shown in Fig. 2 suggest good agreement between the test stands. The values presented in Table 2 show the same trend, keeping the different temperature level of the DLR measurement in mind.

Table 2 Heat losses of the receivers e_{400} = 8.9%/ 9.3% at 400°C

Receiver e_{400} = 8.9%	Absorber temp. (°C)	Ambient temp. (°C)	Heat loss (W/m)
DLR	395	22	213
NREL	400	25	238
Schott (e_{400} = 9.3%)	400	34	237

For the same reasons as mentioned above, Schott measurements from the stored receiver with similar optical properties (e_{400} = 9.3% instead of 8.9%) are presented. Considering the slightly higher emissivity, results seem consistent with the other test stands as well.

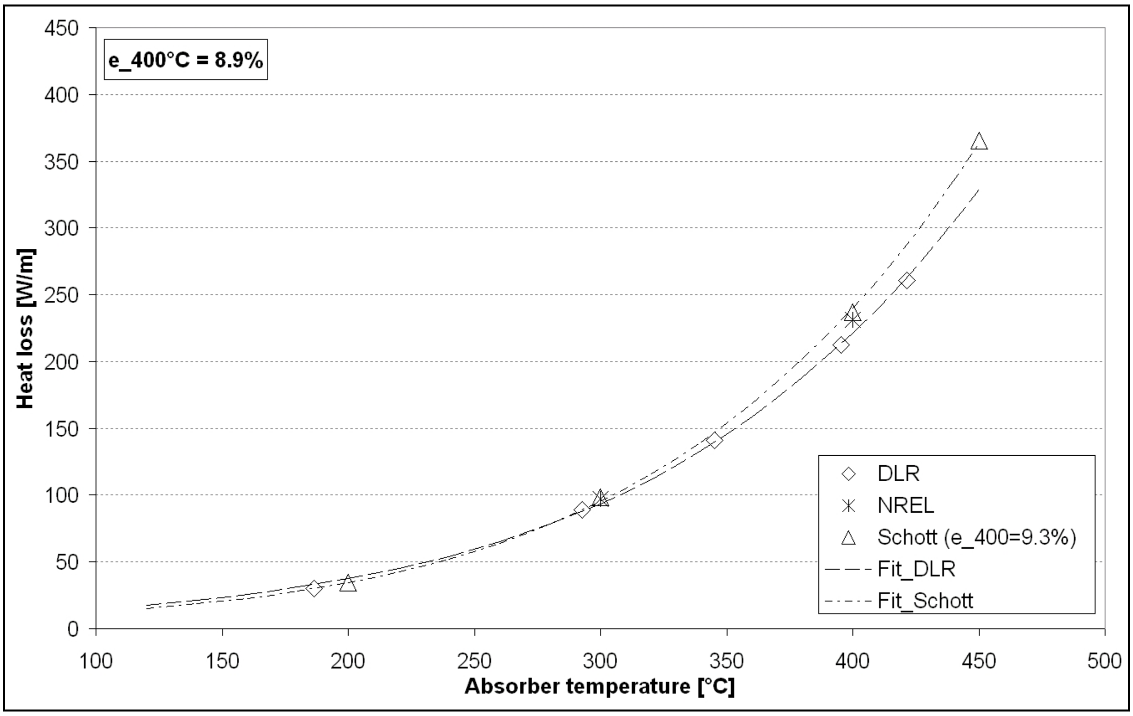

Fig. 2 Heat loss measurement, e_{400} = 8.9%/ 9.3%

Results from the third measured receiver with a relatively high emissivity is presented in Fig. 3 and Table 3. Corrected by the different temperature level, the different measurements show similar results again.

Table 3 Heat losses of the receivers e_{400} = 11.1%/ 11.4% at 400°C

Receiver e_{400} = 11.1%	**Absorber temp. (°C)**	**Ambient temp. (°C)**	**Heat loss (W/m)**
DLR	410	24	275
NREL	400	25	267
Schott (e_{400} = 11.4%)	400	25	272

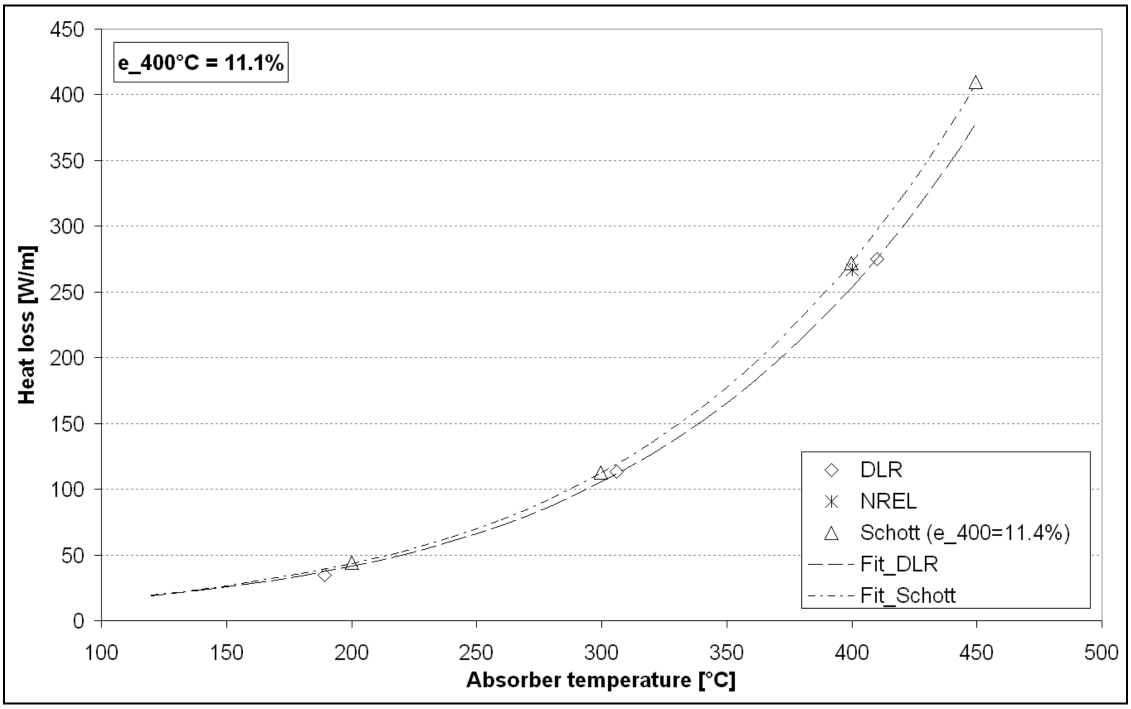

Fig. 3 Heat loss measurement, e_{400} = 11.1%

Overall, results from DLRs measurements show systematically slightly lower heat losses than NRELs. This might be due to differences in the insulation of the receiver.

4. Consistency with optical measurements

4.1. Optical measurements

The optical characterization of the coated absorber tubes is done with an optical measurement system specially designed for the investigation of cylindrical samples. The measured quantity is the spectral reflectance R(λ) of the coated tubes at room temperature (stabilized at T = 20°C). The solar absorptance α is calculated from R(λ) by weighted integration with the solar spectrum AM1.5 in the wavelength range from 305nm to 2500nm. The thermal emittance ε (T) of the coated steel tubes is calculated from R(λ) via the weighted integration with the black body radiation distribution in the wavelength range of 305nm to 30µm at a given operating temperature of the solar field. The emittance values, named for the receivers above, are calculated for a temperature of T = 400°C. ε and α are mean values, calculated over several single measurements over the complete receiver length.

To be able to compare the results of the round robin test with the results of the optical measurements, heat loss values had to be translated into emittances. This translation follows the general concepts of heat transfer [2], i.e. that heat transfer between absorber tube and glass tube equals heat transfer from the glass tube to ambient:

$$\varepsilon_{abs} = \frac{1}{\frac{\sigma}{C_1} - \frac{d_{abs}}{d_{gl}} \cdot \left(\frac{1}{\varepsilon_{gl}} - 1 \right)}; \quad C_1 = \frac{HeatLoss}{\left(\pi \cdot d_{abs} \cdot \left(T_{abs}^{\ 4} - T_{gl}^{\ 4} \right) \right)}$$

This correlation assumes only radiation as heat transfer mechanism influenced by the type of coating at the outer surface of the absorber tube. Therefore heat loss results from NREL, corrected by the end losses, were taken, given that the dominant factors for the end losses are heat transfer mechanisms independent of the coating quality.

4.2. Simulation

To gain confidence in the heat loss measurement principle and verify the results, they were compared to a simulation based on Forristall's heat transfer model of a parabolic trough receiver [1]. This simulation is based on the basic principles of heat transfer. The main input parameter for the simulation of heat loss are the coating properties, namely the emittance at 100°C and 400°C absorber temperature. These values were taken from the optical measurements described in chapter 4.1.

4.3. Results and discussion

Optically measured values and emittance values based on the heat loss results are summarized in Table 4.

Table 4 Comparison of emittance in %, optically measured and calculated values based on the heat loss measurements

Receiver No.	Optical	DLR	NREL	Schott
1	7.0	7.8	7.9	7.9
2	8.9	9.1	9.3	9.9 (compared to 9.3 optical)
3	11.1	10.8	10.9	11.6

As can be seen, differences between optical measurements and heat loss measurements are smaller than absolute 1% emittance. Under the circumstances mentioned in chapter 4.1 and the missing end loss correction of the DLR and Schott results, this lies within the respective errors. The results also suggest that with smaller emittances, differences between optical and thermal measurements increase. Present assumptions are that the relative error of the optical measurements increases with decreasing emittance values. This has to be further investigated once detailed error analyses of all heat loss test stands are present.

The juxtaposition of the heat loss values and optical values translated into heat loss via the use of the simulation, shown in Fig. 4, should illustrate similar trends in the results but may help to visualize the differences.

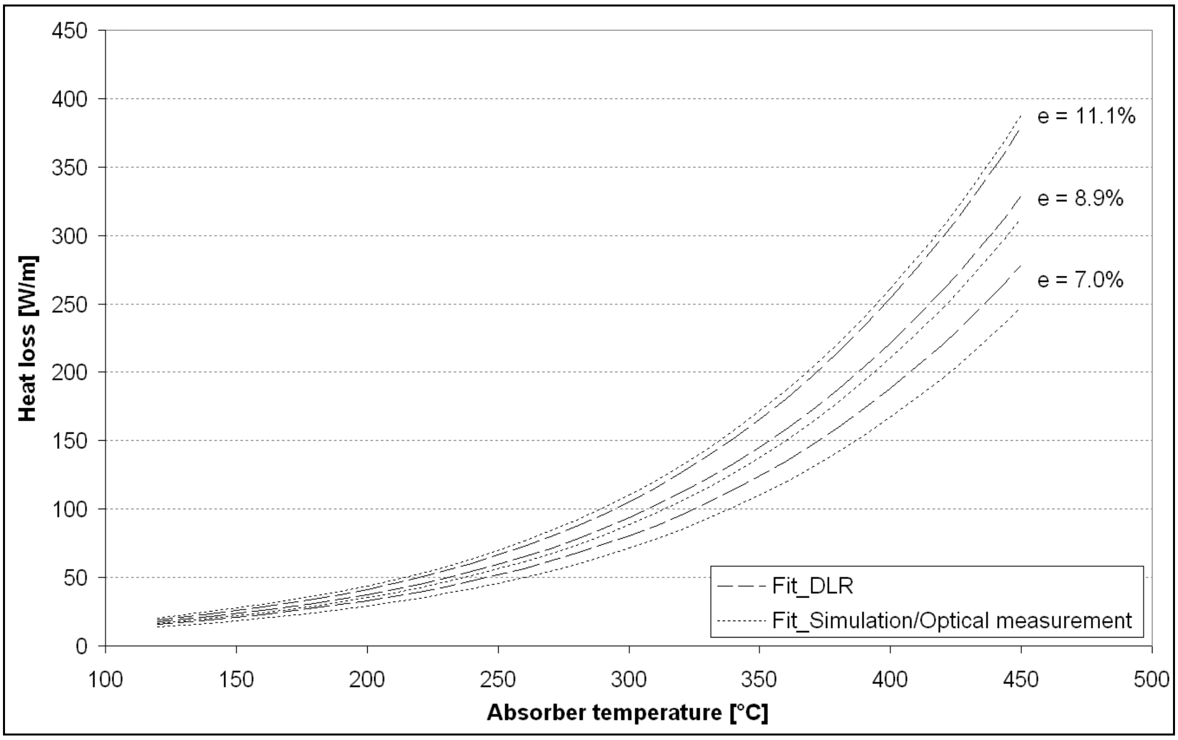

Fig. 4 Simulation versus measurement

Results displayed in Fig. 4 show, that the simulated heat losses tend to be lower than the measured heat losses. This might also be due to the nature of the simulation describing ideal conditions.

The results show sufficiently good agreement between the different measurement setups at Schott, DLR and NREL. However the modeling results are not as consistent as expected. Deviations are assumed to arise from the model being based on the optical measurements and lacking details at the receiver ends including in particular the bellow and its shield configuration.

5. Conclusion

The results of the measurements of receiver heat loss power in different setups shows a good agreement of the measurements. The fast and easily applicable method with Joule heating of the absorber tube has proven its viability and reasonable agreement with the setups used at the laboratories of NREL and DLR.

Subsequently to the detailed error analysis (including end loss determination) to be made for the Schott device, another set of different receivers should be measured again with all three test stands to gain more confidence in the results. Several improvements to the test stand were made since the measurements at Schott and therefore the three traveling and the three stored receivers will be measured again to determine possible shifts in the measurement.

In addition, more detailed Standard Test Conditions, particularly for the end insulation, have to be developed. This should significantly reduce differences between the respective set-ups.

Despite above mentioned challenges still to be solved, results prove that the measurement principle and its diverse implementation in test devices can be a reliable standard method to quantify technical parameters of parabolic trough receivers in the future.

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References

[1] R. Forristall, (2003). Heat Transfer Analysis and Modeling of a Parabolic Trough Solar Receiver Implemented in Engineering Equation Solver, National Renewable Energy Laboratory, Golden, U.S.

[2] G. Cerbe, G. Wilhelms, Technical Thermodynamics, 14 (2005), Hanser, Germany.

Lüpfert E., Riffelmann K.-J., Price H., Burkholder F., Moss T.: Experimental Analysis of Overall Thermal Properties of Parabolic Trough Receivers. J. Sol. En. Eng. Vol. 130, 2008