Conference Proceedings

Solar World Congress 2015
Daegu, Korea, 08 – 12 November 2015

DEVELOPMENT AND TESTING OF A NOVEL METHOD FOR THE DETERMINATION OF THE EFFICIENCY OF CONCENTRATING SOLAR THERMAL COLLECTORS

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Abstract

The objective of this research is the development, evaluation and analyzation of a new test method, called “rapid test method”, for fast and inexpensive assessment of concentrating collectors. The rapid test method aims to derive the instantaneous efficiency curve of a parabolic trough collector. Therefore, a new reference parabolic trough collector was designed and installed at a test rig in accordance with ISO 9806. The determination of the instantaneous efficiency curve according to the rapid test method was compared to the efficiency curve based on ISO 9806. The comparison shows that the rapid test method delivers reproducible and reliable values for the characteristic curve of linear concentrating collectors. The obtained results are within the limits of the measurement uncertainty of a characteristic curve based on ISO 9806. Therefore, the method can be regarded as reliable, inexpensive and easy to use alternative to the conventional measuring method.

Keywords: Rapid test method, ISO 9806, instantaneous efficiency curve, concentrating solar collector, parabolic trough collector, process heat, receiver testing

1. Introduction

The project "Development and testing of a novel method for determining the efficiency of concentrating solar thermal collectors" aims to examine, analyze and optimize the novel test method, called “rapid test method”, for small size parabolic trough collectors.

The conventional test method to evaluate the efficiency of solar thermal collectors requires high cost for the testing equipment, material and sensors. In addition, the test method requires a large number of sunny days that comply with the criteria of the standard. With the novel rapid test method the determination of performance data in the development phase of parabolic trough collectors can be conducted in a rapid, smart and inexpensive manner. Compared to the conventional measurement method in accordance to the ISO 9806:2013 standard, the application of the rapid test method can help to accelerate development steps, reduce cost and encourage small and medium-sized enterprises to tap the market segment of concentrating solar thermal collectors.

The theoretical and practical testing of the rapid test procedure is performed on a newly established test rig. Among others the test rig is equipped with a reference parabolic trough collector in order to ensure a high degree of comparability of the measurements.

2. The rapid test method

The rapid test method uses the results of two independent measurements - the stagnation temperature and the heat losses - to calculate the instantaneous efficiency curve of a parabolic trough collector. With the results of these measurements the efficiency curve can be numerically derived. Figure 1 illustrates the sequence of this approach.

The first set of measurements comprises the measurement of the stagnation temperature of a parabolic concentrator and the ambient air temperature at different levels of irradiation. The stagnation temperature is

doi:10.18086/swc.2015.10.21 Available at http://proceedings.ises.org

defined as the temperature where the system is at a steady state and in the thermal equilibrium with the environment. The irradiated energy from the sun on the collector is equal to the thermal losses, resulting in a collector efficiency of zero. The determination of the stagnation curve is carried out without water or oil as a heat transfer medium, but with air. In the absorber tube of the collector to be tested, solely air at atmospheric pressure is used, which highly reduces the complexity of test equipment. The general form of the equation for the stagnation curve is considered as: $f(G_u) = -a\, G_u^2 + b \cdot G_u$ and an example is presented in figure 2.

Secondly, the heat losses of the receiver as a function of the receiver temperature have to be determined. In this measurement a defined heat flow is transferred to the receiver pipe from the inside and the resulting wall temperature is measured. The heat can either be transferred by an electrical heating element or by a heat transfer medium that was heated up by an external heater. The application with an electrical heating element has the advantage that no closed loop for the heat transfer is required. Moreover, the application is regarded as cost effective and accurate. The general form of the equation for the heat loss curve is considered as: $f(\Delta T) = a \cdot \Delta T + b \cdot \Delta T^4$ An example for a typical heat loss curve is given in figure 3.

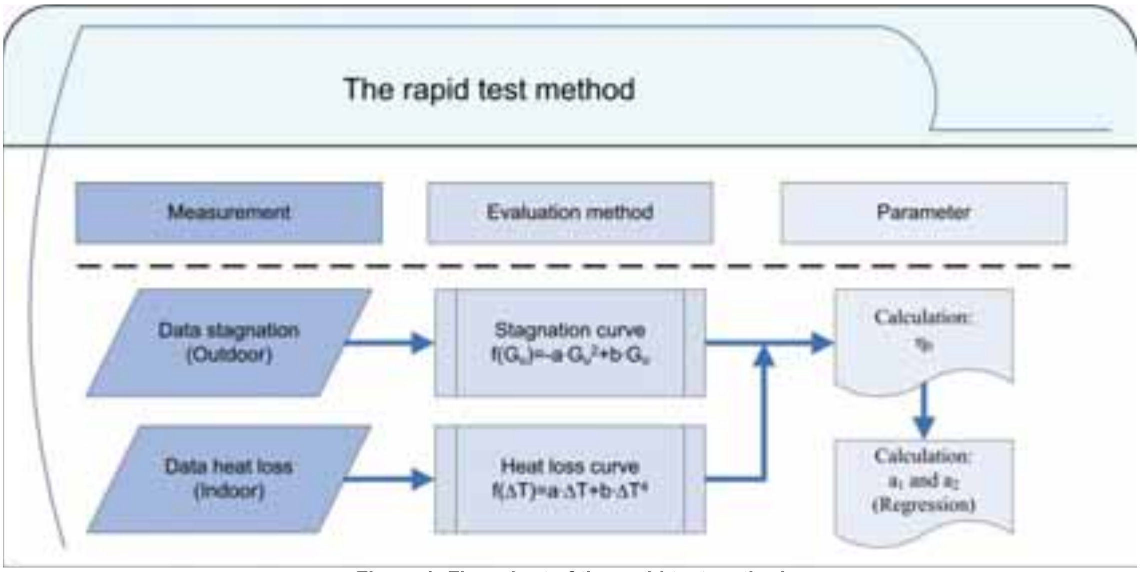

Figure 1: Flow chart of the rapid test method

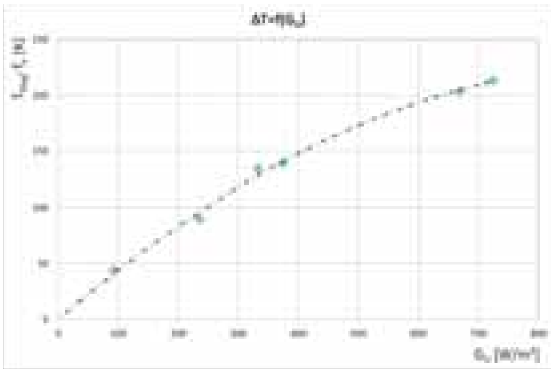

Figure 2: Example for the stagnation curve of a collector at different levels of irradiations

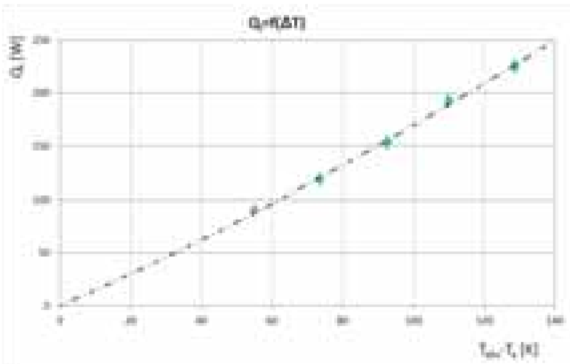

Figure 3: Example of a heat loss curve as a function of *ΔT*

Table 1: Nomenclature of the used indices and its description

Indices	Description	Unit	Indices	Description	Unit
η_0	Optical efficiency	[-]	G	Hemispherical solar irradiance	[W/m²]
η	Instantaneous efficiency	[-]	G_d	Diffuse solar irradiance	[W/m²]
a_1	Heat transfer coefficient	[W/(m²K)]	G_u	Usable solar irradiance	[W/m²]
a_2	Temperature dependence of the heat transfer coefficient	[W/(m²K²)]	G_b	Direct solar irradiance [DNI]	[W/m²]
ΔT	Temperature difference	[K]	Q_y	Thermal yield	[W]
$T_{fl;m}$	Mean fluid temperature	[°C]	Q_l	Thermal losses	[W]
T_a	Ambient temperature (ventilated)	[°C]	T^*_m	Reduced temperature difference	[(m²K)/W]
$T_{fl;Outlet}$	Collector outlet temperature	[°C]	T_{Stag}	Stagnation temperature	[°C]
$T_{fl;Inlet}$	Collector inlet temperature	[°C]	C	Concentration ratio	[-]
T_{Abs}	Absorber temperature	[°C]	A_p	Aperture area	[m²]
T_{corr}	Correction factor	[K]	F'	Collector efficiency factor	[-]

The way how the efficiency curve is derived from these two curves is explained below. Parameters and indices used are given in table 1.

The basic equation for the instantaneous efficiency curve is:

$$\eta = \eta_0 - \left(a_1 \cdot \frac{\Delta T}{G_u} + a_2 \cdot \frac{\Delta T^2}{G_u} \right) \qquad \text{eq.1}$$

Whereas the usable solar energy is defined as / 4 /:

$$G_u = G - G_d + \left(\frac{1}{C} \cdot G_d \right) \qquad \text{eq.2}$$

By introducing eq. 2 for G_u, the diffuse radiation that strikes the receiver's upper surface is also included in the examination. Up to a concentration ratio of approximately 50, the non-observance produces a non-negligible error. Moreover this approach allows the definition of the exact ratio between diffuse and hemispherical irradiation for different values of irradiance. For the rapid test method the temperature difference between stagnation temperature and ambient temperature is considered as ΔT:

$$\Delta T = T_{Stag} - T_a \qquad \text{eq.3a}$$

Whereas at the ISO based method the temperature difference is stated as:

$$\Delta T = \left(\frac{T_{fl;Outlet} + T_{fl;Intlet}}{2} \right) - T_a \qquad \text{eq.3b}$$

The reduced temperature difference is given by:

$$T^*_m = \frac{\Delta T}{G_u} \qquad \text{eq.3c}$$

To calculation the thermal yield of a collector at a certain irradiation and temperature level the following equation is valid:

$$Q_y = A_p \cdot G_u \cdot \eta \qquad \text{eq.4}$$

Consequently the thermal losses at an optional point can be expressed as:

$$Q_l = A_p \cdot G_u \cdot (\eta_0 - \eta) \qquad \text{eq.5a}$$

Hence, for the optical efficiency of a collector the following equation is valid:

$$\eta_0 = \eta + \frac{Q_l}{A_p \cdot G_u} \qquad \text{eq.5b}$$

For the stagnation temperatures measured during the rapid test method, the thermal losses are equal to the energy input into the system and the instantaneous efficiency is equal to zero. $\eta = 0$

From this consideration results the following formula:

$$\eta_0 = \frac{Q_l}{A_p \cdot G_u} \qquad \text{eq.6}$$

The heat loss at various radiation levels can be calculated using a combination of the stagnation curve and the heat loss curve. First, with the determined stagnation curve the temperature difference ΔT can be calculated for the corresponding irradiation. Second, the obtained temperature difference ΔT can be used in the formula of the heat loss curve to calculate the corresponding values. The numerical solution of the thermal loss at various radiation levels is then given by $Q_l=f(G_u)$. With the results obtained the optical efficiency can be calculated for each point i within the interval of the expected solar radiation G_u (0 W/m² $\leq G_u <$ 1000 W/m²). Resulting values for the optical efficiency at different radiation levels are presented in figure 4.

$$\eta_{0,i} = \frac{Q_{l,i}}{A_p \cdot G_{u,i}} \qquad \text{eq.7}$$

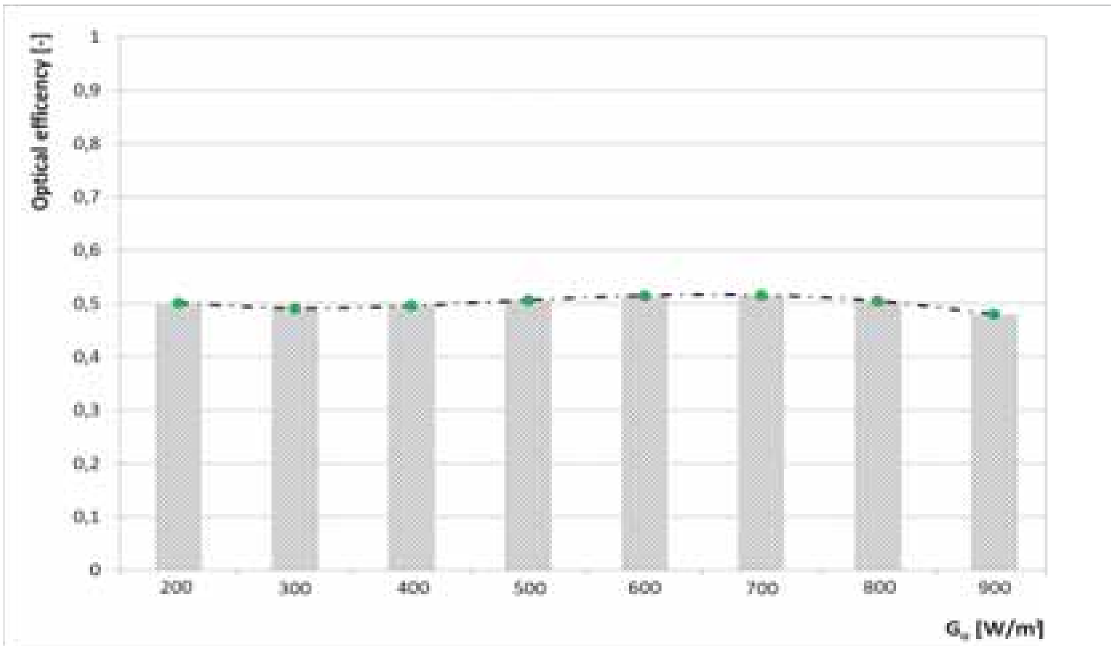

Figure 4: Example for the calculated optical efficiency at different supporting values between the lower and upper limit of the measurements

Uncertainties of measurements occur during the determination of the stagnation curve and the heat loss curve and have an effect on the value of the optical efficiency. The calculated optical efficiency varies slightly for different values of G_u, as shown in figure 4. This variation is based on the combination of two equations, resulting in a higher-order function with a discontinuity at the saddle point of the equation. The mean value of the function of the results obtained for the optical efficiency will give a good approximation for a value η_0 for the further evaluation of the rapid test method. The limits for the integration will be set between the lowest $G_{u,low}$ and highest $G_{u,high}$ measuring point of the stagnation curve.

$$\eta_{0,mean} = \frac{1}{G_{u,high} - G_{u,low}} \cdot \int_{G_{u,low}}^{G_{u,high}} f(G_u) \cdot dG_u \qquad \text{eq.8}$$

When the optical efficiency is determined, the values for the heat loss coefficient a_1 and a_2 can be derived. The heat loss coefficient a_1 and the temperature-dependent heat transfer coefficient a_2 will be calculated by means of a regression in accordance to the least-square method. Since the instantaneous efficiency is set to zero at the stagnation point eq. 1 can be rewritten as:

$$\eta_{0,i} = \left(a_1 \cdot \frac{\Delta T_{,i}}{G_{u,i}} + a_2 \cdot \frac{\Delta T_{,i}^{\ 2}}{G_{u,i}} \right) \qquad \text{eq.9}$$

To transfer the measured results of the rapid test method to real operation, the following three assumptions have to be made:

- A flow of a heat transfer medium through the absorber takes place.
- The operating point is in a steady state at a certain irradiance level and can be standardized to any irradiance level.
- The mean inner absorber tube temperature, which is measured at the rapid test method, is equal to the mean fluid temperature during a test in accordance with the standard. Otherwise a correction factor has to be determined.

$$T_{Abs} = T_{fl,m} + T_{Corr} \qquad \text{eq.10}$$

3. Test setup

At the Solar-Institut Jülich, a test bench infrastructure is operated, which allows to measure individual receiver and small parabolic trough collectors on a biaxial tracking test rig. Measurements of the solar thermal collectors are carried out based on the ISO 9806. The test rig operates with a pressurized water circuit / 1 / at temperatures up to 200 °C and at mass flows up to 200 g/s. The verification of the rapid test method was conducted with a direct comparison to the steady-state measurement method based on ISO 9806:2013. All tests were performed at the same collector with an identical receiver and insulation. The receiver openings shall be sealed to prevent free convection. Furthermore, a suitable number of measurement points in the absorber tube have to be chosen in order to determine a meaningful reference temperature. Figure 5 shows the test rig for the operation of the parabolic trough collector, which is in accordance with ISO 9806:2013. In figure 6 a reference parabolic trough collector is presented. The examined collector can biaxial tracked towards the sun during the tests and the incident angle can be checked and documented automatically by a heliosensor.

Figure 5: Test rig for conditioning of pressurized water and the data acquisition unit

Figure 6: Biaxial rotating test platform with an installed reference collector

4. Results

In July 2014 the first measurements following the rapid test method and the conventional measurements according to ISO 9806 were taken at the SIJ. Both measurements were done at the same collector prototype in order to compare the results of the rapid test method with the ISO based method.

The concentration factor of $C \sim 25$ of the tested collector refers to an absorber tube diameter $\varnothing_a$ of 35 mm. The aperture dimension is 966 mm x 1688 mm. A reflective aluminum sheet was used as reflector. The receiver of this PTC consists of a black chrome coated absorber tube and a glass envelope tube without vacuum insulation. Over the period of the measurement time a reproducible efficiency curve was determined. Efficiency curves were developed with both methods, with the rapid test and the ISO 9806 method. With both curves yearly yield calculation were performed exemplarily for a biaxial tracking collector in Würzburg / Germany using the Energy Output Calculator ScenoCalc / 10 /.The deviation between both results was below 4.0%, based on an operating temperature at 50 °C, 75 °C and 100 °C.

For the rapid test method various criteria were defined, in order to evaluate measurement points during a steady-state phase. First measurements of the collector time constant returned values up to 3 min. This means that the temperature compensation of the receiver and its components requires a comparatively long time until it is in a thermal equilibrium with the environment. In the beginning the criteria as shown below in Table 2 derived from the ISO 9806 were applied. However, this resulted in occasional deviations in the evaluation. The results are distributed over a larger interval of measurement uncertainty. Since the stability of the measured stagnation temperature over time is the most important parameter for the evaluation, a more stringent criterion for the stability of the measured temperature was introduced for further measurements. The tolerable deviation of T_{Stag} was reduced to ± 0,5 °C/min, in return 1 min of stable conditions is enough to get one measurement point. An analysis of the available data with the criteria of the approach 2 gave a better approximation of the characteristic curve from the rapid test method towards the characteristic curve in accordance to ISO 9806.

Table 2: Criteria for the evaluation of measurements points according to the rapid test method

Criteria	Limit value approach 1	Limit value approach 2	Comment
T_a	± 0,5 °C of mean value	± 0,5 °C of mean value	Derived from measurements
G	$G_d/G_U \leq 30\%$	$G_U \geq 100$ W/m²	Derived from measurements
T_{Stag} Stability	± 1 °C / min	± 0,5 °C / min	Derived from measurements
time mean values	4 min after stability	1 min after stability	Derived from measurements
Wind *	3 m/s ± 1 m/s	3 m/s ± 1 m/s	On the basis of ISO 9806
G_u	± 50 W/m² of mean value	± 50 W/m² of mean value	On the basis of ISO 9806

*) The dependency of the wind is in accordance with ISO 9806 only relevant, if the receiver is constructed without a glass envelope tube or if a concentration ratio <3 exists.

It is recommended to determine the time constant before applying the rapid test method in order to obtain a statement about the heating behavior and thus to identify associated conditioning times of the receiver.

In figure 7, the characteristic curve based on ISO 9806 and the curve according to the rapid test method are shown. The calculated stagnation temperature of both methods differs by 4.2 °C at G_u = 1000 W/m² and T_a = 20 °C. The determined measurement points based on the ISO procedure are set in a lower range of the reduced temperature difference, since the corresponding measurements currently limited to an outlet temperature of 200 °C. The measuring points of the rapid test method are in the higher range of the reduced temperature difference, due to the obtained stagnation temperature. For additional information the measurement uncertainty at the respective measuring points are entered. The values are calculated by the Guide of Measurement Uncertainty (GUM). The expanded uncertainty is calculated by multiplying the coverage factor k = 2 with the standard uncertainty of the particular measurement method. The measurement uncertainty is traceable to the specifications and the results from the calibration of the used sensors. The calculated measurement uncertainties are given in the table 3 below.

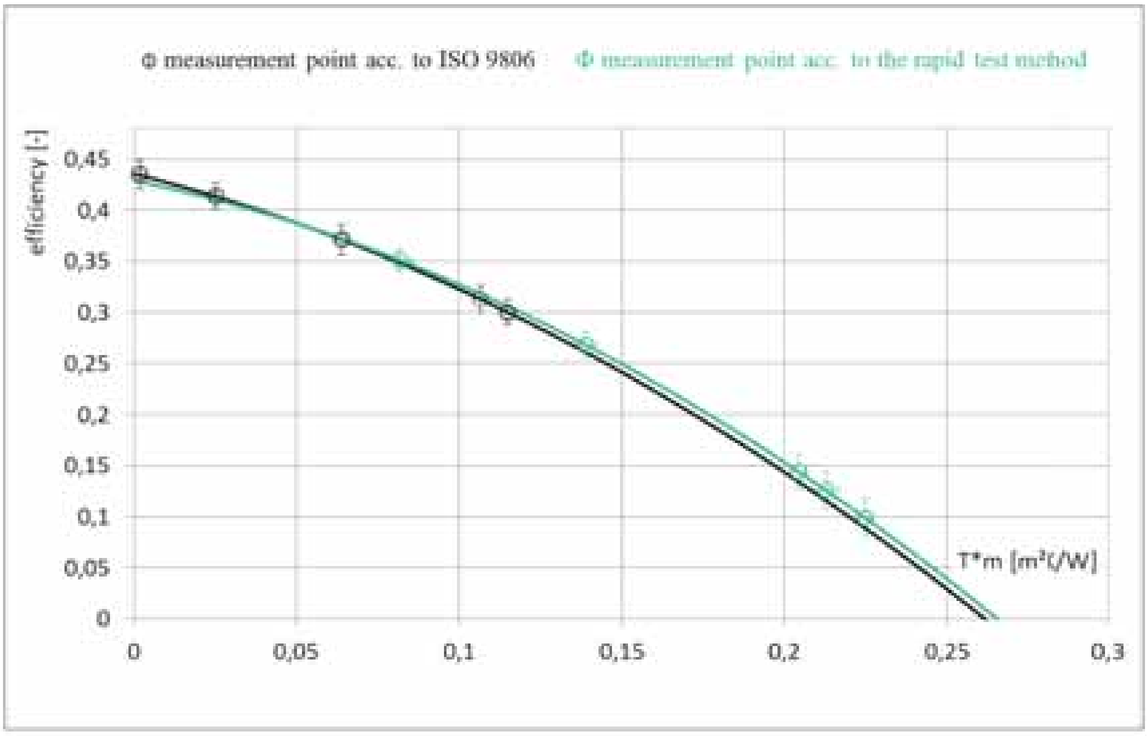

Figure 7: Diagram of the characteristic efficiency curve according to the steady state ISO 9806 method and the rapid test method at G_U of 1000 W/m²

Table 3: Values of the reduced temperature difference, the instantaneous efficiency and the values of the expanded measurement uncertainty displayed as absolute error for the selected operating points

Based on ISO 9806 Absolute error	T^*m [(m²K)/W]	0,00178 ± 0,0002	0,02506 ± 0,0005	0,06380 ± 0,0014	0,10651 ± 0,0022	0,11490 ± 0,0023
	η [-]	0,435 ± 0,014	0,414 ± 0,012	0,371 ± 0,015	0,313 ± 0,014	0,300 ± 0,012
Rapid test method Absolute error	T^*m [(m²K)/W]	0,08178 ± 0,0018	0,13884 ± 0,0026	0,20436 ± 0,0037	0,21263 ± 0,0038	0,22477 ± 0,0040
	η [-]	0,351 ± 0,011	0,268 ± 0,013	0,144 ± 0,017	0,126 ± 0,018	0,099 ± 0,019

Furthermore, theoretical calculations and simulations are carried out to determine a correction factor for the rapid test method. Those calculations and simulations are necessary because of the physical conditions during the rapid test, which tend to have a higher mean temperature than the standard procedure. At the rapid test method, the mean temperature of the inner absorber tube is taken as a reference (eq.3a) whereas the ISO 9806 method considers the mean water temperature as a reference (eq.3b). By applying formula eq.10 the transformation towards the ISO curve can be conducted. In chapter 5 the determination of the correction factor is described.

5. Limitations of the rapid test method

Due to the different approach of the rapid test method and the test method based on ISO 9806, a different reference temperature for the calculation is taken into account as a basis for determining the instantaneous efficiency curve. In the rapid test method, the mean temperature inside the absorber pipe is measured during stagnation as a parameter and simultaneously treated as the average collector temperature. However, in the measuring method according to ISO 9806 the useful energy obtained from the collector is calculated by using the average fluid temperature. Owing to the differences in approach, the efficiency curve of the rapid test method is theoretically always higher than the method according to ISO 9806. To evaluate this bias theoretical calculations are performed using a receiver model with a given geometry. Further, FEM simulations to determine a correction factor for the rapid test method are carried out with COMSOL Multiphysics® Modeling Software. Moreover measurements to verify the results of the correction factor were conducted. In applying the rapid test method for absorber tubes of concentrating parabolic trough collectors there is only a slight variation of the considered average collector temperature, depending on the operation point and the mass flow rate. For the results given in figure 7 and table 3 the correction factor was determined for a mass flow of ~75 g/s, which is the mean mass flow during the measurements based on ISO 9806. The values for the correction factor at the figure 7 are between 1,5 °C to 6,5 °C, depending on the reduced temperature difference *T*m*.

$$T_{Corr} = f(\dot{m}; T^{*}m) \qquad \text{eq.11}$$

Since the temperature correction factor is depending on the mass flow, the operating temperature, the ambient temperature and the specific receiver geometry, it must be determined for each receiver individually.

However, collector designs with low collector efficiency factor F' lead to a greater difference between the characteristics of the ISO 9806 and the rapid test. Consequently, a non-negligible error without the use of adapted correction factors will occur.

Since stagnation temperatures are measured in accordance to the rapid test method, very high thermal loads are applied on the coating of the receivers. Most absorber coatings available on the market are only stable below temperatures that are typically reached in the stagnation point at high irradiation values. The resulting thermal stress can lead to new order processes in the layers, increase reaction rates and may cause temperature-dependent diffusion processes within the layer /5/. These processes can lead to destruction, partial degradation by blistering or a change in the optical properties of the absorber coating. Table 4 gives an initial, non-exhaustive overview of different absorber coatings, which are available on the market or are currently in the research stage.

Table 4: Overview of absorber coatings and their temperature stability /3/,/5/,/9/ & /11/

Classification	Medium temperature layers						High temperature layers			
Properties	selective	selective	selective	selective	selective	selective	selective	selective	selective	selective
Product	TiNOx	Sunstrip	Black Chrystal	Chrome-Coat	Black Chrome	Solkote	Ni-Al₂-O₃	Black Cobalt	M_xO_y+M'Fe₂O₃	Black Moly
Functional layer	TiN_xO_y	Ni-NiO	NiSn	Cr-Cr_2O_3	Cr-CrO	Solar coating	Mo-Ni SS	Co_3O_4/Co	n.s.	Mo-MoO_2
Substrate	Cu	Al	Cu	Cu	Cu	V2A, Cu	V2A	n.s.	Ni-Mo alloy	n.s.
α_s	0,95	0,92 -0,97	0,93-0,98	0,97	0,95	0,88-0,94	0,94	0,96-0,92	>0,9	0,94
ε_{th} (100°C)	0,05	0,1	0,08-0,25	0,09	0,12	0,2-0,49	0,07	0,71-0,017	>0,45	0,3 [500°C]
$\alpha_s / \varepsilon_{th}$	19	9,2-9,6	3,92-11,6	10,78	7,92	1,8 - 4,7	13,4		~ 2	3,13
Temperature stability/ degradation air	not specified (n.s.)	300 °C	300°C	350 °C	350°C	-73-538°C	350-400°C	400-650 °C	700 °C	350 °C
Temperature stability/ degradation vacuum	400°C	n.s.	n.s.	400°C	n.s.	n.s.	500°C	n.s.	n.s.	500 °C
Production process	PVD*	Sputtering	Sol-Gel	Elekcro-deposition	Galvano-technique	Spraying	Rf-Sputtering	n.s.	Coating, Plasma	CVD**

) PVD: Physical Vapour Deposition* *) CVD Chemical Vapour Deposition*

Because of this limitation, concentrating collectors are measured during the course of the rapid test method just below the limit of their temperature stability. Measurements of stagnation temperatures takes place at lower irradiation levels in the morning or in the evening. Knowledge of the substrate layer and the functional layer with its technical specifications are thus preconditional for a careful implementation of the rapid test method. For safety reasons the receiver can be instrumented with a temperature sensor and the tracking control unit at the SIJ test rig will drive the parabolic trough out of the focus, if the temperature stability of the absorber is reached.

6. Outlook

The rapid test method delivers reproducible and reliable values for the characteristic curve of linear concentrating collectors. The obtained results are within the limits of the measurement uncertainty of a characteristic curve based on ISO 9806.

Therefore, the method can be regarded as reliable, inexpensive and easy to use alternative to the conventional measuring methods. For the testing season 2015, further comparative measurements are planned at different types of receivers and parabolic trough collectors in order to gather further experience in the implementation of the rapid test method and to check the procedure with different PTC designs.

Moreover the determination of the stagnation curve and the heating curve will be optimized in order to reduce the measurement uncertainties of the methods. Further optimization will be carried out by analyzing different regression approaches to reduce the statistical spread of the calculated optical efficiency.

7. Acknowledgement

The project is carried out within the framework of the Federal Ministry of Education and Research (BMBF) program FHprofUnt. The authors are grateful for this support.

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