Topic report for WP2 Solar thermal collectors

Experience from tests on concentrating and tracking collectors

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Summary of work carried out, main results and proposals for standard revision

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QAiST
Quality Assurance in Solar Heating and Cooling Technology

1 Summary

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This report summarises the work carried out within the QAiST project in the field of concentrating and tracking collectors. The aim of this work was the introduction and validation of a test method capable to treat concentrating as well as concentrating and tracking collectors with the same accuracy as the current standard treats flat plate and evacuated tubular collectors.

Section 2 (Introduction) points out the major issues to keep in mind when dealing with concentrating and tracking collectors.

Section 3 (Test of CPC collectors) describes the quasi-dynamic collector model and points out the necessity to distinguish between diffuse and beam irradiance when testing concentrating collectors.

Section 4 (Test of parabolic trough collectors) applies the implemented procedure to two different parabolic trough collectors and shows that these measurements have the same accuracy as the results for conventional flat plate and evacuated tubular collectors.

Section 5 (Experience in dynamic testing of a concentrating collector) describes the experience made by an additional test laboratory.

Section 6 (End losses of linear concentrating collectors) summarizes equations used to calculate the end losses of single modules as well as the end gains achieved when several modules are installed in series.

Section 7 (Text proposals for standard revision) list the main text which needs to be included in the next revision of the EN 12975. Besides the necessary terms and definitions related to concentrating and tracking collectors the changes to the existing test procedure is described and equations describing the thermal properties of water up to a temperature of 185 °C and a pressure of 12 bar are given.

Section 8 (Proposal for future work) lists from the point of view of the consortium the five most pressing issues for further work needed to bring forward the technology of mid temperature collectors including tracking and concentrating collectors. These five topics are:

1. Cooperation between stakeholders of different technologies
2. Components
3. In-situ measurements
4. Round Robin testing up to 200 °C
5. Phase change liquids

Annex A (Working paper on impact of wind speed on concentrating collectors during performance measurement) describes the work and calculations done to determine the impact of the wind speed to concentrating collectors depending on the emittance of the absorber coating and the concentration ratio.

Annex B (Working paper on performance measurement at elevated temperatures) summarizes the topics to keep in mind when testing collectors at temperatures above 100 °C.

2 Introduction

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Concentrating as well as concentrating and tracking collectors need special attention during performance testing. The three main reasons are:

1. Different influences on the conversion factor η_0 compared to flat plate and evacuated tubular collectors.
2. Different incidence angle modifier compared to flat plate and evacuated tubular collectors.
3. The strong impact of the concentration factor on the performance under diffuse irradiance

This chapter gives a short introduction to the three mentioned items.

2.1 Definition of the conversion factor

The conversion factor η_0 for flat plate and evacuated tubular collectors is defined by the product of the collector efficiency factor F' and the transmission-absorbance-product $(\tau\alpha)$ (equation 1).

$$\eta_0 = F'(\tau\alpha) \tag{1}$$

For concentrating and concentrating and tracking collectors the reflectivity ρ of the reflector and the intercept factor γ (fraction of reflected radiation which is intercepted by the receiver) reflecting the tracking and reflector accuracy has to be taken into account as well (equation 2).

$$\eta_0 = F'(\tau\alpha)\rho\gamma \tag{2}$$

2.2 Incidence angle modifier for concentrating and tracking collectors

Stationary CPC collectors

CPC collectors do have, like evacuated tubular collectors a biaxial behaviour with respect to beam irradiance. However due to the acceptance angle of the CPC reflector which depends on the concentration factor C the incidence angle modifier is changing significantly within only a few degrees.

Table 1 and figure 1 show the incidence angle modifier in longitudinal and transversal plane for the CPC collector as described in section 3.

Table 1: Incidence angle modifiers for a CPC collector

θ	0	10	15	20	25	30	35	40	60	90
$K_{b\theta}(\theta_l,0)$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.78	0.0
$K_{b\theta}(0,\theta_t)$	1.00	0.97	0.99	0.93	0.84	0.53	0.36	0.33	0.06	0.0

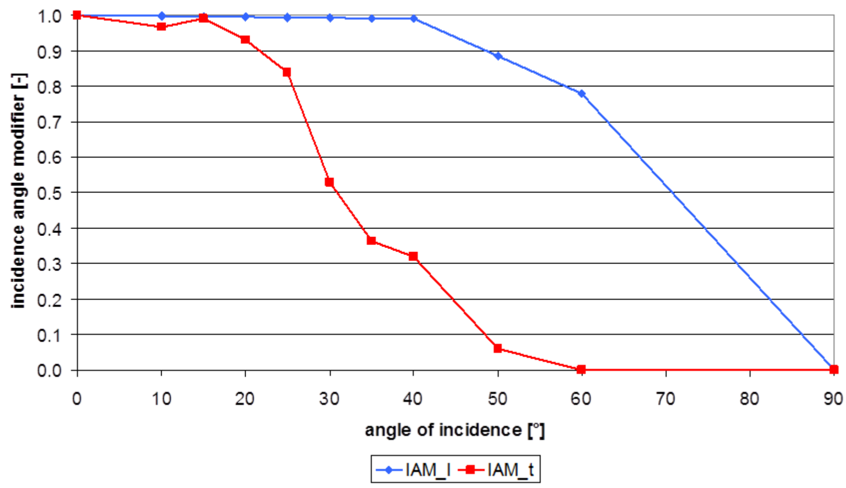

Figure 1: Incidence angle modifiers for a CPC collector

Concentrating and tracking collectors

For concentrating and tracking collectors basically three different incident angle modifier models apply:

1. A bi-axial incidence angle modifier similar to evacuated tubular or CPC collectors Applies for linear Fresnel collectors.

2. For e.g. parabolic trough collectors the bi-axial behavior reduces due to the one axis tracking to one axial behaviour. In this case the longitudinal incidence angle is the incidence angle of the collector since the transversal angle of incidence is always kept at 0° by the tracking mechanism.

3. For two-axis tracking collectors the angle of incidence is always kept at 0° and thus the incidence angle modifier by definition to 1.

2.3 Impact of diffuse irradiance on the performance of concentrating collectors

The thermal performance of concentrating collectors depends among others strongly from the concentration ratio C. The concentration ratio for collectors having tubular absorbers is calculated by the ratio between aperture area and unrolled absorber area. Simplified it can be assumed that the diffuse irradiance available for the collector is reduced by the quotient 1/C. Using this assumption the irradiance G_{net} which can be used by the collector can be calculated using equation 3.

$$G_{net} = G_{beam} + \frac{1}{C} G_{dfu} \tag{3}$$

Dividing the useable irradiance G_{net} by the hemispherical irradiance G yields the useful fraction N described by equation 4.

$$N = \frac{G_{net}}{G} = \frac{G_{beam} + \frac{1}{C} G_{dfu}}{G} \tag{4}$$

Due to this dependence of the useful irradiance G_{net} on the concentration ratio C more diligence has to be taken for the determination of the thermal performance of concentrating collectors compared to flat plate collectors.

Figure 2 shows the useful fraction of the hemispherical irradiance N over the concentration ratio C for different diffuse fractions $D = G_{dfu}/G$. High concentration ratios and high diffuse fractions yield to a low value of useful irradiance fraction.

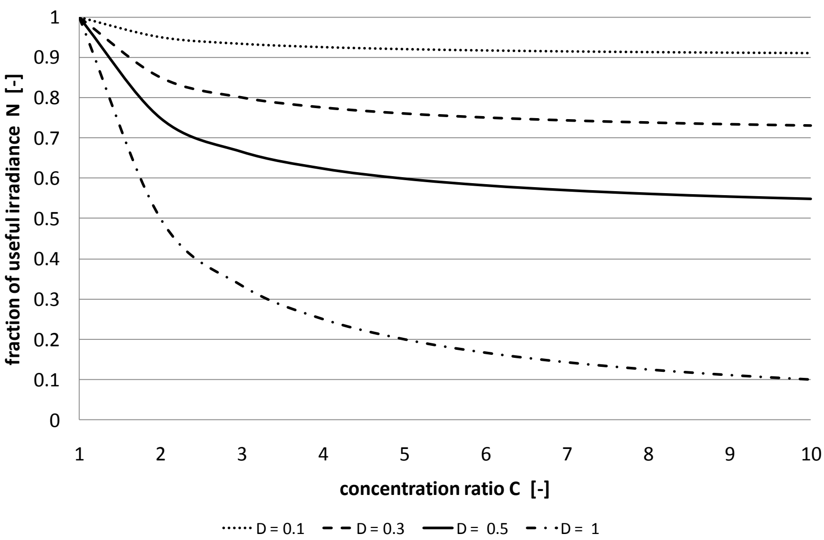

Figure 2: Fraction of useful irradiance N as a function of the concentration ratio C and the diffuse fraction D

Nomenclature

C	[-]	Concentration ratio
D	[-]	Diffuse fraction
F'	[-]	Collector efficiency factor
G	[W/m²]	Hemispherical irradiance
G_{dfu}	[W/m²]	Diffuse irradiance
G_{dir}	[W/m²]	Beam irradiance
G_{net}	[W/m²]	Useful irradiance
N	[-]	Fraction of useful irradiance
γ	[-]	Intercept factor
ρ	[-]	Reflectance
η_0	[-]	Conversion factor
θ	[-]	Angle of incidence
$(\tau\alpha)$	[-]	Transmittance-absorptance-product

3 Test of CPC Collectors

Within this section the performance measurement of two different CPC collectors, the first one having a normal bi-axial IAM behaviour and the second having a multi-axial IAM behaviour, are described.

3.1 CPC Collector 1

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CPC collectors (see figure 1) are using a Compound Parabolic Concentrator as reflector in order to concentrate the solar irradiance on the absorber. Due to this concentration CPC collectors have, in comparison to the aperture area, a smaller absorber area which results in smaller heat losses. With reference to the operating temperature, CPC collectors therefore present a logical link between flat plate collectors and evacuated tube collectors.

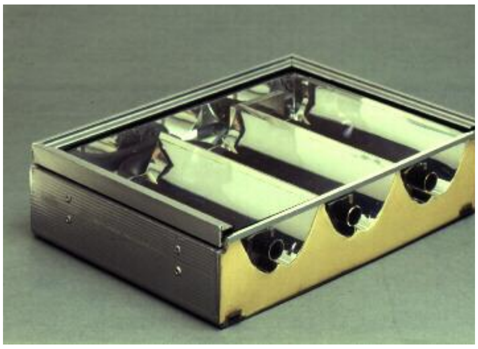

Figure 1: CPC collector

CPC collectors available on the market usually have a concentration ratio in the range of C = 1 - 2. These concentration ratios, however, result in a smaller conversion of the diffuse irradiance compared to flat plate and evacuated tube collectors. During the determination of the thermal performance of CPC collectors this fact must be taken into account.

The European standard EN 12975-2:2006 [1] allows for different test methods to determine the thermal performance of solar thermal collectors. Right now the test method under steady state conditions as well as the method under quasi-dynamic conditions are used to determine the thermal performance of CPC collectors.

The present section compares the results gained with the two different test methods. The comparison will show that the method under steady state conditions is not suitable to determine the thermal performance of CPC collectors correctly.

Test method

The European Standard EN 12975-2:2006 allows for two test methods for the determination of the thermal performance. The test method under steady state conditions and the test method under quasi-dynamic conditions.

The more detailed test method under **quasi-dynamic conditions** differentiates between beam irradiance G_{beam} and diffuse irradiance G_{dfu}. Together with the incidence angle modifier for beam irradiance $K_{beam}(\theta)$ and diffuse irradiance K_{dfu} it is therefore possible to model the influence of the beam irradiance under different incident angles as well as the dependency of the thermal performance on the diffuse fraction. In addition the implementation of the effective heat capacity c_{eff} in the thermal performance model of the collector (see equation 1) allows the description of the dynamic behaviour of the collector under changing radiation levels. By means of the test method under quasi-dynamic conditions the thermal performance of stationary non-concentrating collectors can be determined as well as for tracking concentrating collectors. The relatively high level of detail of the model permits the use of test sequences with strong variation in the level of irradiance.

The simplified test method under **steady state conditions** abstains from the differentiation of the beam and diffuse irradiance and the metrological determination of the effective heat capacity (see equation 2). The major drawback of these simplifications is the fact that only data that was recorded under very constant (steady state) conditions can be used for evaluation. An additional uncertainty in the test results is created by the use of an incident angle modifier for the hemispherical irradiance $K(\theta)$ which itself depends on the diffuse fraction prevailing during the measurements. Due to these simplifications the test method under steady state conditions is strictly speaking only suitable for collectors with a thermal performance not depending significantly on the nature of the irradiance (beam or diffuse). Hence the test method is not suitable for concentrating collectors at all.

$$\dot{Q} = A\left(\eta_0 G_{beam} K_{beam}(\theta) + \eta_0 G_{dfu} K_{dfu} - a_1(\vartheta_{fl,m} - \vartheta_a) - a_2(\vartheta_{fl,m} - \vartheta_a)^2 - c_{eff}\frac{d\vartheta_{fl,m}}{dt}\right) \quad (1)$$

$$\dot{Q} = A\left(\eta_0 G K(\theta) - a_1(\vartheta_{fl,m} - \vartheta_a) - a_2(\vartheta_{fl,m} - \vartheta_a)^2\right) \quad (2)$$

For CPC collectors available on the market today with a concentration ratio of 1 < C < 2 the fraction of useful irradiance is reduced up to 25% depending on the diffuse fraction. In the following the impact of this fact on the test results of CPC collectors is described.

Application of the different test methods

A CPC collector having an aperture area of 1.87 m² was analysed. The collector uses a circular absorber tube with an outer diameter of 19 mm. With an aperture width of 103 mm this results in a concentration ratio of C = 1.73.

Table 1 shows the results determined with the tests under quasi-dynamic and steady state conditions. The mean diffuse fraction during the test under steady state conditions was D = 0.3.

Figure 2 shows the power curves calculated using the collector parameters determined under quasi-dynamic conditions for diffuse fractions of 0.1, 0.3 and 0.5 together with the power curve calculated with the collector parameters determined under steady state conditions.

Table 1: Collector parameters determined

	η_0 [-]	K_{dfu} [-]	a_1 [W/(m²K)]	a_2 [W/(m²K²)]	c_{eff} [kJ/(m²K)]
quasi-dynamic	0.798	0.725	3.483	0.009	13.65
steady state	0.725	-	3.599	0.007	-

Figure 2 shows the significant dependency of the collector output from the diffuse fraction D. For a diffuse fraction of D = 0.5 the maximum collector output is reduced by 160 W/m² and 11 % respectively compared to the collector output at a diffuse fraction of D = 0.1.

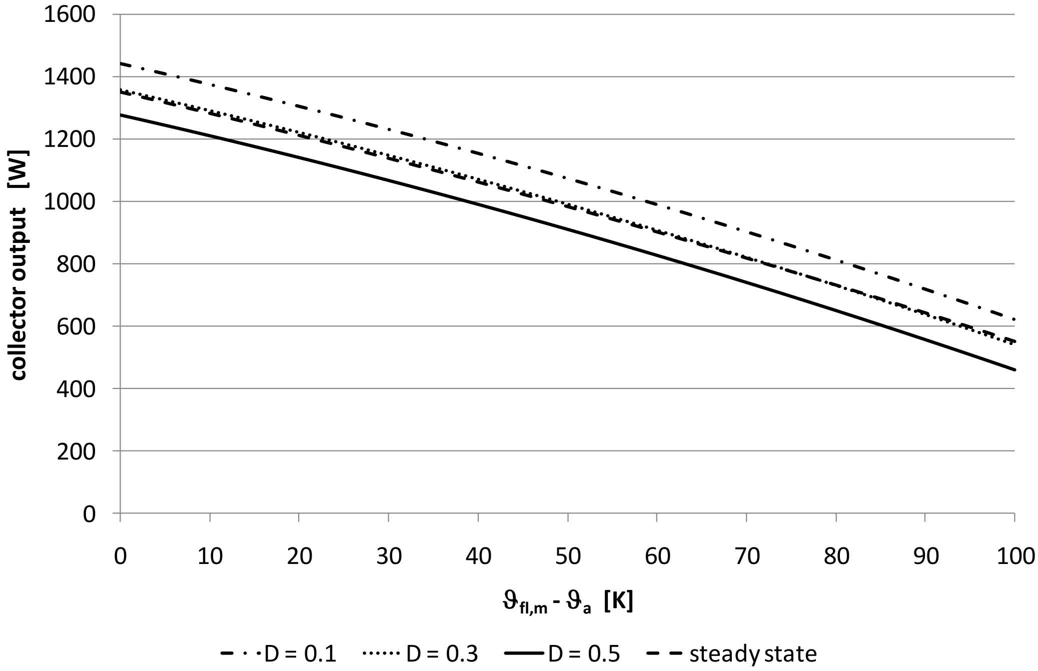

Figure 2: Power curves (G = 1000 W/m²) for different diffuse fractions and under steady state conditions

The power curve determined using the test method under steady state conditions shows a similar appearance as the power curve determined for a diffuse fraction of D = 0.3. This attributes to the fact that the mean diffuse fraction during the test under steady state conditions has been D = 0.3.

From the presented investigation basically two conclusions can be drawn:

1. The collector parameters gained from the test under quasi-dynamic conditions are very well suited to calculate the collector performance for different diffuse fractions.

2. The collector performance calculated from the collector parameters gained under steady state conditions is only valid for the diffuse fraction prevailing during the measurements. The usage of these results leads to an under estimation of the collector output for diffuse fractions smaller and to an over estimation for diffuse fractions larger than the values predominant during the steady state measurement.

Conclusion

The test method under quasi-dynamic conditions is in contrast to the test method under steady state conditions very well suited to determine the thermal performance of CPC collectors having a concentration ratio larger than 1. Especially the differentiation between diffuse and beam irradiance permits a reliable modelling of the thermal performance under various diffuse fractions. The level of detail enables a more exact estimation of the yearly energy gain and thus a higher planning reliability during the dimensioning of solar thermal systems using CPC collectors.

The test method under steady state conditions is not suited for CPC collectors due to the poor reproduction of the incident irradiance. The inaccuracy of the test method even grows with rising concentration factors.

The increasing efforts in the fields of the solar thermal process heat and solar cooling lead to a rising number of concentrating collectors on the European market. Against this background it is appropriate to codify the test method under quasi-dynamic conditions as the sole test method to be used for concentrating collectors within the next revision of the European standard EN 12975.

Nomenclature

a_1	[W/(m²K)]	Heat loss coefficient
a_2	[W/(m²K²)]	Temperature dependent heat loss coefficient
A	[m²]	Aperture area
C	[-]	Concentration ratio
c_{eff}	[J/(m²K)]	Effective heat capacity of the collector
D	[-]	Diffuse fraction
G_{dfu}	[W/m²]	Diffuse irradiance
G_{beam}	[W/m²]	Beam irradiance
$K(\theta)$	[-]	Incidence angle modifier for hemispherical irradiance
$K_{beam}(\theta)$	[-]	Incidence angle modifier for beam irradiance
K_{dfu}	[-]	Incidence angle modifier for diffuse irradiance
$\dot{Q}$	[W]	Collector output
η_0	[-]	Conversion factor
θ	[-]	Angle of incidence
ϑ_a	[°C]	Ambient temperature
$\vartheta_{fl,m}$	[°C]	Mean fluid temperature
t	[s]	time

References

[1] DIN EN 12975-2:2006, Thermal solar systems and components – Solar collectors - Part 2: Test methods -, 2006.

3.2 CPC Collector 2

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Introduction

A 2,2 m^2 aperture area compound parabolic concentrating (CPC) collector was performance tested according to chapter 6.3 of the EN 12975 standard. The multi-axial incidence angle modifier and the general optical properties of the collector where additionally analysed. The peak efficiency for this collector having an offset from the normal of 10-12 degrees in the transverse direction raised some questions around the testing procedure and the way results are reported. Long term measurements where performed on the tested collector using a constant inlet temperature in order to validate the collector model.

The collector

The collector measured is shown in Figure 1 and Figure 2 . It is a light weight construction without insulation and with a double-sided selectively coated fin absorber. It is primarily designed for roof mounting at 10 to 45 degrees tilt but it can also be wall mounted or mounted on a tracker.

Figure 1 The CPC collector's transverse IAM measured with collector in vertical orientation (N-S**)**

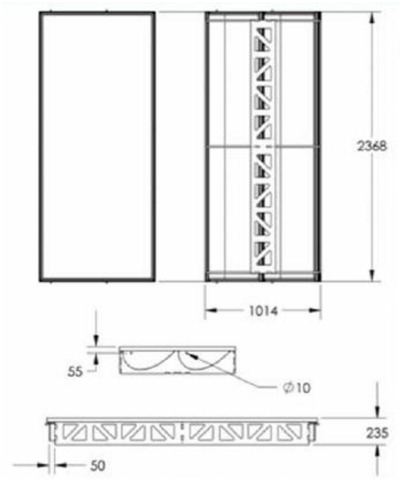

Figure 2 Drawing of the CPC collector

As a means for reducing overheating problems, the particular design of this collector is meant to make it less efficient during the summer months compared to the spring- and autumn period for which it is optimized. This implies that the collector is mounted in the "correct" tilt and in the horizontal, east-west position. The geometrical concentration factor is close to three but effectively 1,6 due to the double-sided absorber.

Performance test and evaluation

Performance testing was carried out with the collector in two fixed position.

1. With the collector oriented horizontally, with the absorber strips in the east-west direction

2. With the collector oriented vertically, with the absorber strips in the north-south direction, see Figure 1.

In the first position the collector was measured at four different inlet temperatures in order to provide data for identification of all parameters except for the transverse IAM. In the second position the efficiency at $t_m - t_a = 0$ was measured to determine the transverse IAM.

The measurements were carried out in September i.e. close to the autumn equinox in order to have a more or less negligible influence of the transverse IAM on the results when determining the longitudinal IAM.

Presentation of results

According to the definition of the IAM, the reference efficiency is the efficiency measured at normal incidence and at $\mathbf{t_m - t_a = 0}$

$$K_\theta \, dir = \frac{\eta(\Theta)_{dir\,(at\, t_m - t_a = 0)}}{F'(\tau\alpha)_{en}}$$

$$K_\theta \, dfu = \frac{\eta(\Theta)_{dfu\,(at\, t_m - t_a = 0)}}{F'(\tau\alpha)_{en}}$$

With indexes “dir” for direct irradiance and “dfu” for diffuse irradiance.

The resulting optical parameters using this definition are shown in Table 1 and the IAM curves are presented in Figure 3.

Table 1: Optical efficiency and IAM for direct and diffuse irradiance using the efficiency at normal incidence as reference

$F'(\tau\alpha)_{en}$ = 0.42[1] [-]				$K_{\theta d}$ = 1.020 [-]						
θ	**0**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**
$\mathbf{K_{\theta T}}$	1	1.52	1.48	1.42	1.39	1.38	1.25	1.1	0.55	0
$\mathbf{K_{\theta L}}$	1	1	0.98	0.98	0.93	0.90	0.76	0.55	0.27	0

[1] $F'(\tau\alpha)_{en}$ = 0.42 corresponds to Solarus with the optical axis in north south position to determine the collector efficiency factor at normal incidence.

θ	0	-10	-20	-30	-40	-50	-60	-70	-80	-90
$K_{\theta T}$	1	0.65	0.57	0.52	0.45	0.34	0.15	0.12	0.08	0
$K_{\theta L}$	1	1	0.98	0.98	0.93	0.90	0.76	0.55	0.27	0

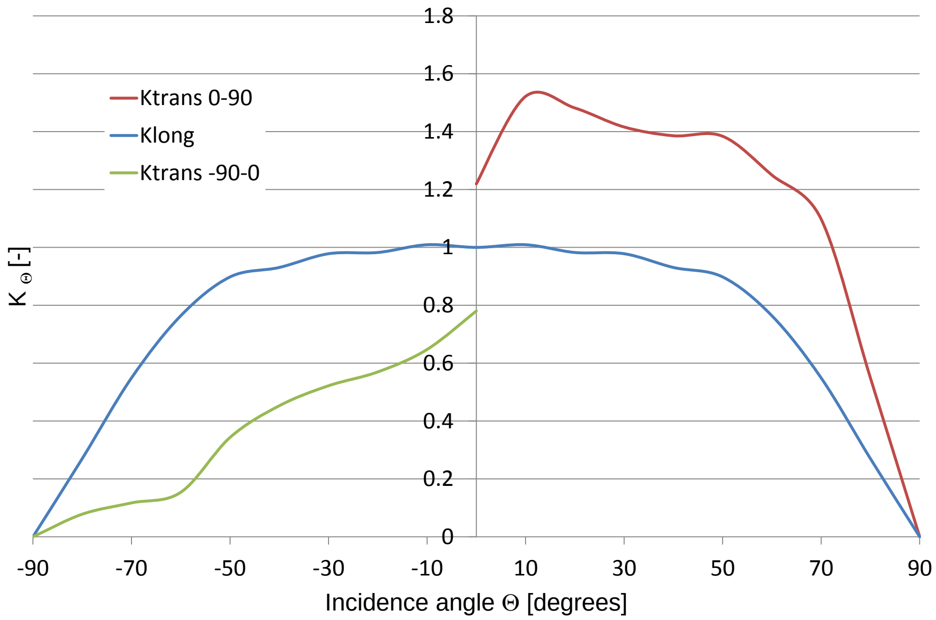

Figure 3 Transverse and longitudinal IAM referring to the efficiency at normal incidence

Model validation

A validation of the collector model used for testing and performance prediction was carried out by means of three months of measurements on the collector using a constant inlet temperature close to 50°C. In fact the performance prediction was carried out using the Scenocalc tool developed in the QAiST project. Results in terms of hourly values are shown in Figure 4.

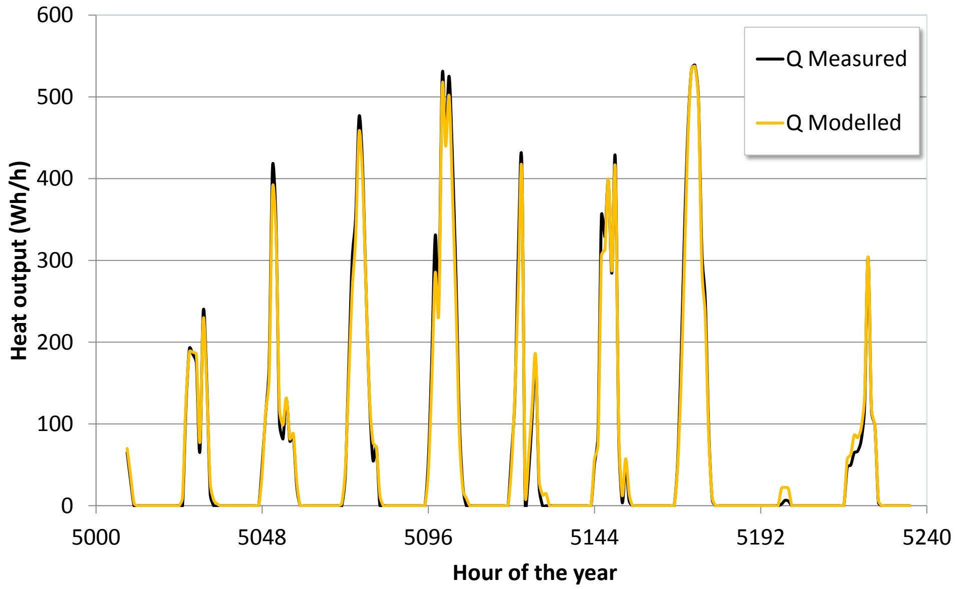

Figure 4: Hourly values of measured and modelled performance of the CPC collector

On an average the deviations between modelled and measured output tend to level out each other very well. Accumulated energy yield for a three month period is presented in Figure 5 showing relative deviations of 0,5; 2,7 and 3,5 % for July, August and September respectively. On an hourly timescale the relative deviations can however be significant.

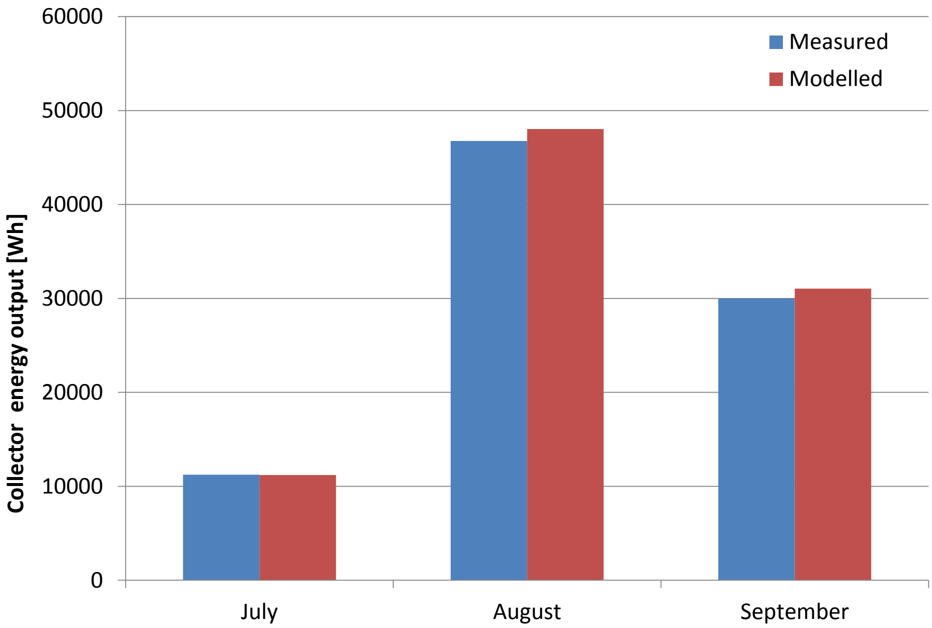

Figure 5: Measured and modelled monthly energy yields for the tested CPC collector. All monthly results show agreement better than 5%.

4 Test of Parabolic Trough Collectors

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This section describes the performance measurements of two parabolic trough collectors that have been carried out during the development of the test method described in section 7.2.

4.1 First test of a parabolic trough collector

The collector efficiency of a parabolic trough collector prototype has been tested according to the European Standard EN 12975. The Standard includes, apart from the well-known steady state parameters, an incident angle modifier for diffuse irradiation and an effective collector thermal capacity. The addition of these two collector parameters allows the evaluation of continuous measurements over several hours even under irradiance fluctuations and changing sun position.

Introduction

The thermal performance of a solar collector is of major interest to all parties, e.g. designer, investor, operator and last but not least collector manufacturer, involved in the setup of a solar thermal system. In order to be able to compare the thermal performance of different collectors a standardized test method must be available. Standardized test methods have been published in international normative documents for decades1,2. These Standards are well accepted for the test of flat plate collectors and evacuated tubular collectors. However if it comes to collectors with a significant concentration ratio the stipulated use of the hemispherical solar irradiance as reference irradiance does not meet the requirement for the performance characterization anymore. To overcome this difficulty the “concentrating community” uses the direct irradiance as reference irradiance together with the test procedures [1], [2] to characterize the thermal performance of concentrating collectors. This non-normative approach leads to a variety of collector models as well as differing nomenclatures and methodologies. The first attempt to standardize these different approaches was done by all major institutions involved in the performance testing of tracking concentrating collectors [3].

With the implementation of the European Standard EN 12975 [4] an alternative test method under so called quasi-dynamic conditions has been introduced. This test method, in contrast to previous ones takes into account direct irradiance as well as diffuse irradiance and thus permits the performance measurement of tracking concentrating collectors.

In order to further develop the test method under quasi-dynamic conditions for concentrating and tracking collectors a parabolic trough collector has been tested. For the purpose of this work the test identity was eliminated by introducing an arbitrary scale factor.

Collector model

The collector output is modeled with 6 parameters using the following equation [4].

$$\frac{\dot{Q}}{A} = \eta_0 K_{\theta b}(\theta) G_b + \eta_0 K_{\theta d} G_d - c_1(\vartheta_m - \vartheta_a) - c_2(\vartheta_m - \vartheta_a)^2 - c_5 \frac{d\vartheta_m}{dt}$$

In contrast to the Standards [1], [2] the hemispherical irradiance G is divided into the direct G_b and diffuse G_d parts. For both irradiances an incident angle modifier is used. $K_{\theta b}(\theta)$being a function of the angle of incidence of the direct irradiance and the constant $K_{\theta d}$ for the diffuse irradiance. The conversion factor η_0 is the efficiency of the collector at ambient temperature under steady state conditions. The thermal losses are modeled by a 2nd order polynomial approach, c_1 and c_2 being the heat loss coefficients corresponding to the temperature difference between the mean fluid and ambient temperature and the square of the temperature difference respectively. The effective collector capacity c_5 accounts for the transient behavior of the solar collector and permits measurements under changing levels of irradiance. The introduced effective thermal capacity permits continuous measurements even under scattered cloud conditions.

Collector test

The test facility used allows for testing up to a temperature of 250°C. Two axis normal tracking ($K_{\theta b}(0) = 1$) was active throughout all sequences of the test. In order to operate the collector array at different conditions five test sequences have been used covering clear sky conditions as well as scattered clouds. The mean fluid temperature varied from close to ambient up to 175 °C. The length of the test sequences varied between four and seven hours. Table 1 summarizes the conditions of the five test sequences used for the parameter identification.

Table 1: Test sequences used for parameter identification

Test sequence	Duration [min]	Mean fluid temp [°C]	Sky condition
1	360	35	Clear sky
2	420	35	Scattered clouds
3	240	115	Clear sky
4	290	150	Mainly clear sky
5	300	175	Clear sky

Figures 1 and 2 show the direct irradiance G_b, diffuse irradiance G_d and the specific collector output P_{col} per aperture area during two test sequences.

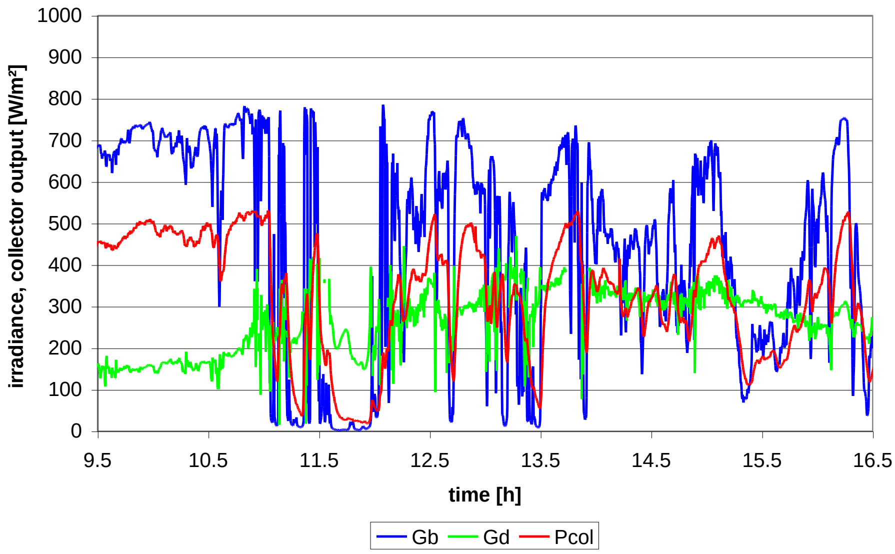

Figure 1: Test sequence 2, unstable irradiance

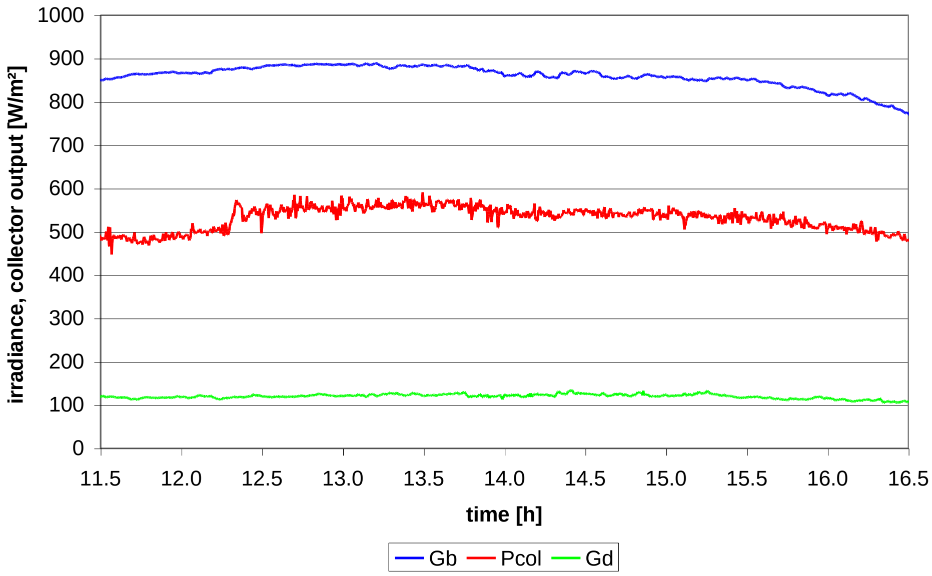

Figure 2: Test sequence 5, on a clear day

Parameter identification and results

For the evaluation of the measured data Multiple Linear Regression (MLR) as the parameter identification tool is foreseen [4]. MLR uses a fast, non-iterative matrix method. However, other algorithms, mainly used for non-linear models, lead to the same results and will be allowed as parameter identification tool in the next review of the Standard. A comparison of the MLR method and the iterative method has been published [7]. The advantage of the iterative method is a high flexibility with respect to the input data as well as to the collector model. For this study the DF program [5] was used. It uses the Levenberg–Marquardt algorithm [6] for the parameter identification process.

Table 2 shows the parameter set determined from five test data series. In Figure 3 the measured and calculated collector output for test sequence 1 is plotted. The dynamics of the measured collector output are very well described by the five collector parameters.

Table 2: Determined collector parameter

η_0 [-]	$K_{\theta d}$ [-]	c_1 [W/(m²K)]	c_2 [W/(m²K²)]	c_5 [J/(m²K)]
0.674	0.179	0.211	0.002	12680

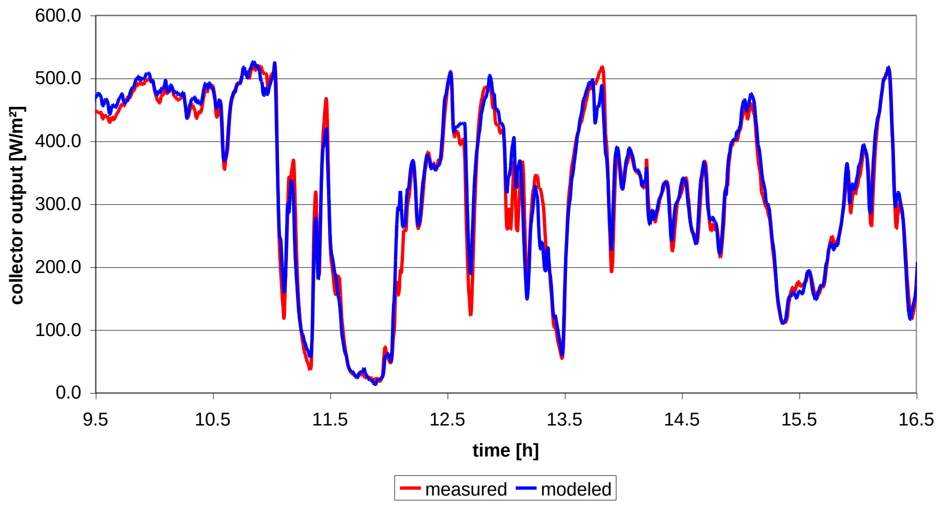

Figure 3: Measured and modeled collector output of test sequence 2

Conclusion

A parabolic trough collector prototype has been efficiency tested according to EN Standard 12975 using the test method under quasi dynamic conditions. This test method allows varying ambient conditions and continuous measurements over the day. This is possible because a collector model is used that takes into account the effective collector capacity as well as the diffuse irradiance on the aperture plane. The results show a very good agreement between measured and modeled collector output. An overall testing time of 5 days only in part under clear sky conditions, was sufficient to extract the relevant collector performance parameter set.

With the use of the European Standard EN 12975 a performance testing not only for flat plate or evacuated tubular collectors but also for all tracking and concentrating collectors is possible.

Nomenclature

Symbol	Unit	Description
A	m²	Area
b	m	Collector width
C_{geo}	-	Geometric concentration ratio b/πd
c_1	W/(m²K)	Heat loss coefficient at $(t_m - t_a) = 0$
c_2	W/(m²K²)	Temperature dependence of the heat loss coefficient
c_5	kJ/(m²K)	Effective thermal capacity
$d\vartheta_m/dt$	K/s	Time derivative of the mean fluid temperature
d	m	Absorber tube diameter
G	W/m²	Hemispherical solar irradiance
G_b	W/m²	Direct (beam) irradiance
G_d	W/m²	Diffuse irradiance
$K_{\theta b}(\theta)$	-	Incident angle modifier for beam irradiance
$K_{\theta d}$	-	Incident angle modifier for diffuse irradiance
P_{col}	W	Useful output power
Q	W	Useful output power
η_0	-	Conversion factor
ϑ_a	°C	Ambient temperature
ϑ_m	°C	Mean fluid temperature
θ	°	Incident angle of the beam irradiance

References

1 ASHRAE 93-77, *Methods of Testing to determine the thermal performance of solar collectors*, American Society of Heating, Refrigeration and Air Conditioning Engineers. New York, 1977

2 ISO 9806:1994, Test methods for solar collectors - Part 1: Thermal performance of glazed liquid heating collectors including pressure drop, Part 2: Qualification test procedures

3 Lüpfert E, Herrman U, Price H, Zarza E, Kistner R, *Towards standard performance analysis for parabolic trough collector fields*, Proceeding SolarPaces Conference Oxaca, 2004

4 EN 12975-2:2001, Thermal solar systems and components – Solar collectors. Part 2: Test methods, CEN Brussels, 2001

5 Spirkl W, *Dynamic SDHW system Testing, Program Manual,* Sektion Physik der Ludwig-Maximilians Universität München, 1994.

6 Press W, Teukolsky SA, Vetterling WT, and Flannery BP, *Numerical Recipes, second Edition.* Cambridge University press, 1992

7 Fischer S, Heidemann W, Müller-Steinhagen H, Perers B, *Collector parameter identification – iterative methods versus multiple linear regression*, ISES Solar World Congress, Gothenburg, 2003.

4.2 Second test of a parabolic trough collector

Stephan Fischer (fischer@itw.uni-stuttgart.de)

The test described in section 4.1 was carried out with two-axis tracking. As a consequence, the incidence angle modifier could not be determined. The second test was carried out on a parabolic trough aligned in east-west direction with a one-axis tracking system of the supplier of the parabolic trough collector.

Performance Testing

Test set-up and conditions

The investigated system was a parabolic trough collector (figure 1) for process steam generation operated with pressurised water.

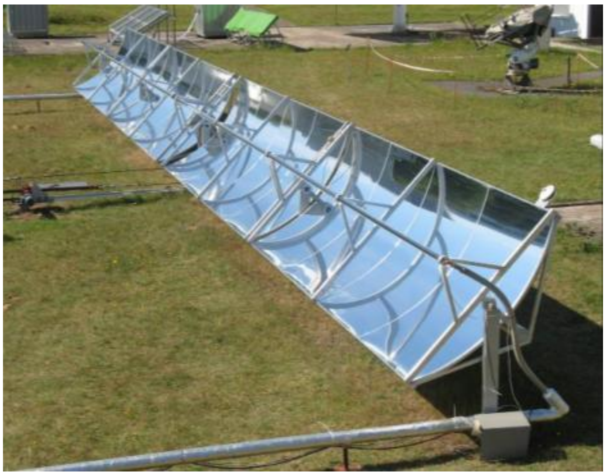

Figure. 1: Parabolic trough collector under test

Table 2 gives an overview of performance testing conditions.

Table 2: Performance Testing Conditions

Test Day	Inlet Temperature	Weather Conditions
#1	40°C	clear sky
#2	130°C	clear sky
#3	155°C	clear sky, small clouds
#4	100°C	clear sky
#5	36°C	clear sky
#6	120°C	partly overcast after solar noon

Performance measurements

The useful thermal collector output corresponds to the increase in fluid enthalpy and is calculated from the measured mass flow rate, temperatures at the inlet and outlet, and fluid specific heat capacity according to

$$\dot{Q}_{gain} = \dot{m} \cdot \bar{c}_p (T_{out} - T_{in}) \quad (1)$$

and modelled afterwards according to

$$\frac{\dot{Q}_{gain}}{A} = \eta_0 \cdot K_{\theta b}(\theta) \cdot G_b + \eta_0 \cdot K_{\theta d} \cdot G_d - c_1 \cdot (T_m - T_a) - c_2 (T_m - T_a)^2 - c_5 \cdot \frac{dT_m}{dt} \quad (2)$$

The results of the parameter identification of quasi-dynamic collector performance testing are stated in Table 3.

Table 3: Collector parameters according to quasi-dynamic testing

model parameter	units	Value
η_0	-	0.682
$K_{\theta d}$	-	0.04
c_1	W/m²K	0.176
c_2	W/m²K²	0.004
c_5	J/m²K	3019

In quasi-dynamic analysis optical collector efficiency is distinguished with respect to the nature of the irradiance. While optical efficiency for beam irradiation is clearly an important characteristic of a collector the relevance of diffuse irradiance for concentrating systems is strongly depending on the concentration factor C (see chapter 2 Introduction). The possible contribution of the latter is limited to a fraction of the incident diffuse radiation determined by the concentration ratio of the system.

Multi-Linear Regression is best suited to multivariate model equations of linear independent quantities. In the case of performance equations with several heat loss terms all depending on the temperature difference to the surroundings and powers thereof there is a strong dependence of quantities to be fitted. This leads to high sensitivity of the parameters to slight deviations in measurement points (uncertainty) and hence increased parameter uncertainty. In order to make the parameter identification more robust it is worthwhile considering the elimination of some of the terms provided this does not compromise the overall fit quality.

The identification of the effective heat capacity of an installation from quasi-dynamic test data is challenging for two reasons: Most importantly, due to the restriction in testing conditions changes in mean system temperature are small and can be masked by signal fluctuations. Furthermore, because of the typically small changes in temperature the capacitive term only contributes very little to the target value that is used in the minimization criteria, i.e. the specific collector output. Consequently, the uncertainty of c_5 is typically quite high. Nevertheless, values identified by parameter identification are physically consistent and of the expected order of magnitude compared to theoretical values.

Incidence Angle Modifier

Collector performance is always referenced to the irradiance on the aperture area, thus already including the effect of the angle of incidence as cosine factor. The additional influence of the angle of incidence of the incoming solar irradiance on the collector output is expressed as the incidence angle modifier (IAM), either by means of a complete function or using discrete nodes and interpolating in-between. The latter is particularly advantageous when investigating more complex collector geometries like linear Fresnel systems. A possible function describing the IAM is a polynomial of the absolute value of θ:

$$K_{\theta b}(\theta) = b_0 + b_1 \cdot \theta + b_2 \cdot \theta^2 + b_3 \cdot \theta^3 \qquad (8)$$

Table 3 summarizes the IAM values derived from the measurements using the two different approaches.

Table 4: IAM function parameters and nodes

IAM function parameters				
parameter	b_0	b_1	b_2	b_3
units	-	$(°)^{-1}$	$(°)^{-2}$	$(°)^{-3}$
Value	1	$-5.782\ 10^{-3}$	$1.485\ 10^{-4}$	$-2.955\ 10^{-6}$
IAM nodes				
angle	0°	20°	40°	60°	90°
value	1	0.92	0.83	0.59	0

As illustrated in Figure 2 deviations in resulting IAM values are small compared to data uncertainty. They can be further decreased by adding nodes in the relevant range of angles of incidence, provided there is sufficient test data.

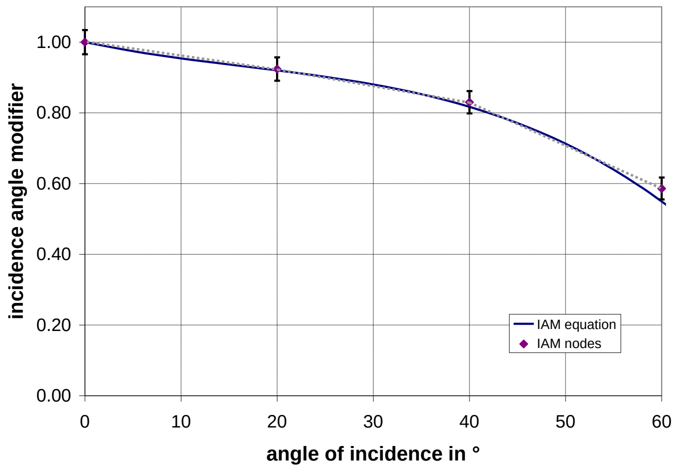

Figure 2: Collector IAM as a function of angle of incidence comparing the IAM equation and node approach

For further work the IAM model using nodes should be preferred because of the higher flexibility.

Comparison between measured and calculated collector output

Figures 3 and 4 show the comparison between measured and calculated collector output as well as the difference of both. It can be stated that the model and method is very well suited for testing of concentrating and tracking collectors.

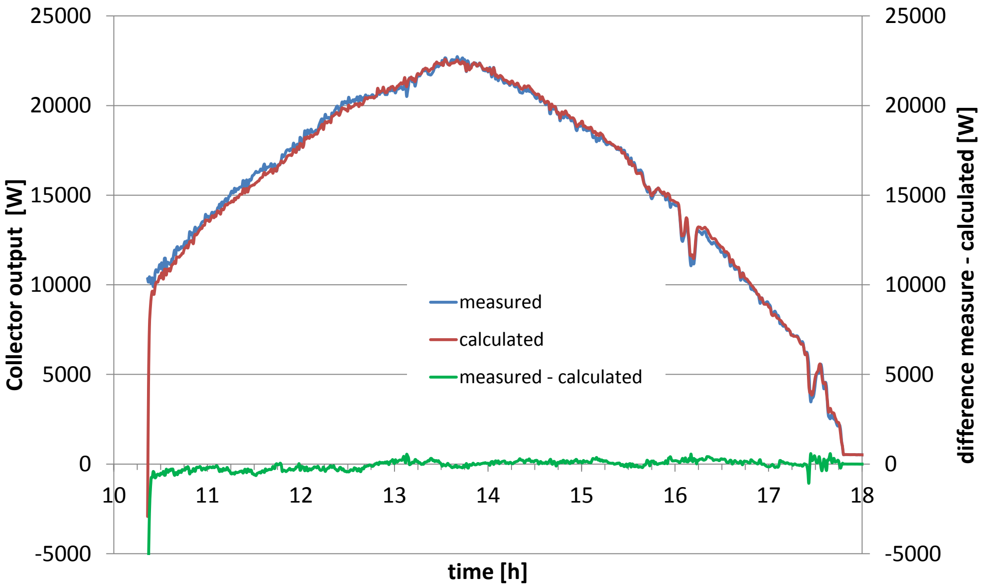

Figure 3: Measured and calculated collector output for test day #5 according to table 1

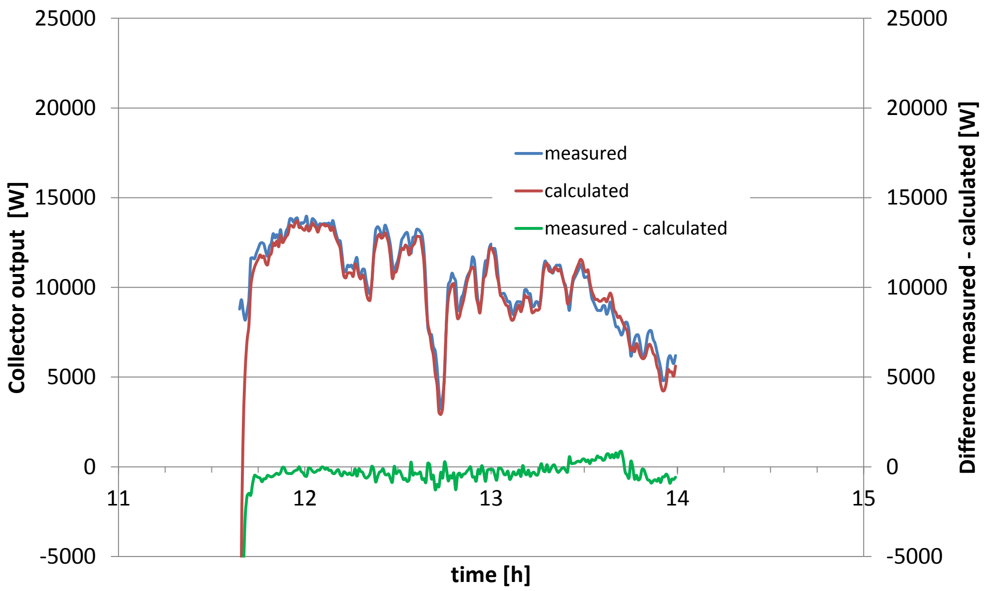

Figure 4: Measured and calculated collector output for test day #6 according to table 1

Symbols

a_1, a_2	K m²/W, (K m²/W)²	thermal loss parameters
A	m²	aperture area
b_0, b_1, b_2, b_3	-,(°)$^{-1}$,(°)$^{-2}$,(°)$^{-3}$	empirical coefficients of IAM function
c_1, c_2, c_5		empirical collector parameters (heat loss, effective heat capacity)
c_p	J/(kg K)	specific heat capacity
G_d, G_b	W/m²	direct irradiance, beam irradiance (normal to collector aperture)
$K_{\theta b}(\theta)$	-	incidence angle modifier for beam irradiance
$K_{\theta d}$	-	incidence angle modifier for diffuse irradiance
$\dot{m}$	kg/s	mass flow rate
$\dot{Q}_{gain}$	W	heat gain
t	s	time
T_{in}, T_{out}, T_a, T_m	°C	fluid inlet, outlet, ambient, mean temperature
η_0	-	conversion factor
θ	°	angle of incidence

5 Experience in dynamic testing of a concentrating collector

Korbinian Kramer (Korbinian.Kramer@ise.fraunhofer.de)

Collector model

The standard collector model in EN12975-2 Chapter 6.3.4.8.2 was used as the basis of all considerations.

$$Q/A = F'(\tau\alpha)_{en} K_{\theta b}(\theta)\, G_b + F'(\tau\alpha)_{en} K_{\theta d}\, G_d - c_6\, u\, G^* - c_1 (t_m - t_a) - c_2 (t_m - t_a)^2 - c_3\, u\, (t_m - t_a) + c_4 (E_L - \sigma T_a^4) - c_5\, dt_m/dt$$

Because of the fact, that the absorbing surface is not facing the sky and is much smaller than the aperture area, the long wave irradiance was not considered and coefficient c4 was eliminated from the beginning.

According to chapter 6.3.4.8.3 the coefficients c3 and c6 were included because the T-Ratio was shown to be greater than 2.The T-Ration of coefficient c2 was shown to be smaller than 2 and therefore it was eliminated.

The equation is thus reduced to

$$Q/A = F'(\tau\alpha)_{en} K_{\theta b}(\theta)\, G_b + F'(\tau\alpha)_{en} K_{\theta d}\, G_d - c_6\, u\, G^* - c_1 (t_m - t_a) - c_3\, u\, (t_m - t_a) - c_5\, dt_m/dt$$

Irradiance measurement

Because the aperture of the collector consists of 24 tracked reflectors and theta for every single reflector is neither equal nor known or constant over the daytime, the global irradiance was measured in the plane in which the reflectors are suspended.

This plane is tracking the zenith angle, thus the longitudinal theta for this plane is 0 at high noon. The direct irradiance was measured with a pyrheliometer and computed into this plane with the cosine-function.

The diffuse irradiance was calculated as the difference between global and direct irradiance in this plane.

Incidence angle modifier (IAM)

The definition of the IAM as $K\theta = (\tau\alpha)e\theta \,/\, (\tau\alpha)en$ has to be modified for this collector. In this case the IAM accounts for the following effects:

- Tracking accuracy
- Angle-dependence of reflectance of the mirrors
- Angle-dependence of absorption

- Angle-dependence of shading effects (moving shade of the absorber on the reflectors, possible shading between the different reflectors themselves in transversal direction)
- Angle-limitation of the tracking device

The collector has a bidirectional IAM. Due to the tracking of the zenith angle, the longitudinal IAM is being considered to be 1 at all times.

Since the transversal angle-dependence of the collector is unknown, the equation

$K_{\theta b}(\theta) = 1 - b_o((1/\cos\theta_i) - 1)$

cannot be used.

Instead the zero-loss-efficiency is being directly determined for different classes of incidence angles with an extended MLR. In this case the values for direct irradiance were separated into classes of 10°.

The maximum tracking angles of the system, respectively the incidence angles where the system goes to security position, have to be considered (in this case no values with an incidence angle greater than 65° have been accounted for). Therefore $K_{\theta b}$ has to be 0 for these angles.

6 End losses of linear concentrating collectors

Stephan Fischer (fischer@itw.uni-stuttgart.de)

In addition to the optical losses due to optical dependency of glass, absorber mirrors, etc. from the angle of incidence (see equation 1 according to Beckmann), linear concentrating collectors underlie additional losses caused by the geometry, the so-called end losses.

$$\cos\theta = \sin\phi(\sin\delta\cos\beta + \cos\delta\cos\gamma\cos\omega\sin\beta) + \cos\phi(\cos\delta\cos\omega\cos\beta - \sin\delta\cos\gamma\sin\beta) + \cos\delta\sin\gamma\sin\omega\sin\beta \quad (1)$$

With

θ = Angle of incidence
ϕ = Latitude of location
δ = Declination angle
β = Slope
γ = Azimuth angle
ω = Hour angle

End losses occur at the ends of linear concentrating collectors. When solar radiation, by non-zero angles of incidence, reaches an end of a linear concentrating collector, the length l of the absorber tube is not illuminated by solar radiation reflected from the mirrors (Figure 6**:**). Thus the focus is beyond the length of the absorber tube (Trieb, et al., 2004), (Muthusivagami, 2011).

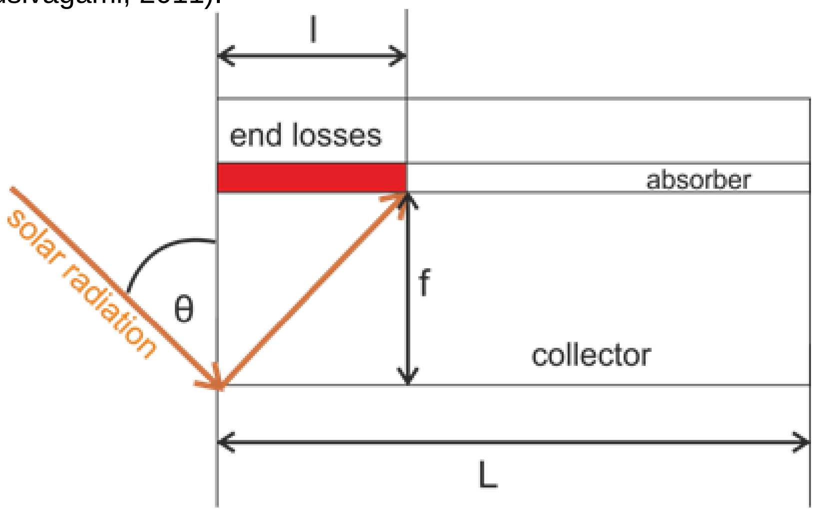

Figure 6: Geometric sketch of a parabolic trough

End losses are a function of the focal length f of the collector, the angle of incidence θ and the collector length L. The losses are greatest when the sunrays are parallel to the orientation of the linear concentrating collectors and have a small height angle. This situation mostly occurs in the morning and evening (Trieb, et al., 2004). The length l of the absorber tube which is not illuminated is calculated to (Larcher, 2012)

$$l = f \cdot \tan\theta \qquad (2)$$

With

f = focal length (parabolic trough collector) or height of receiver (fresnel collector)

In several references the end loss is defined according to equation (3), see (Muthusivagami, 2011) and (Patnode, 2006).

$$End\ loss = 1 - \frac{l}{L} = 1 - f\,\frac{\tan\theta}{L} \qquad (3)$$

With

L = length of the linear concentrating collector

This definition is misleading, because actually end losses are the ratio of l to L. In this publication the definition in equation (4) is introduced.

$$IAM_{endloss} = 1 - \frac{l}{L} = 1 - f\,\frac{\tan\theta}{L} \qquad (4)$$

Another definition of the end losses are given by (Beckmann, et al., 2006), see equation (5).

$$IAM_{endloss} = 1 - \frac{f}{l} \cdot \left(1 + \frac{a^2}{48 f^2}\right) \cdot \tan\theta \qquad (5)$$

With

a = aperture width of the trough collector

The term $\left(1 + \frac{a^2}{48 f^2}\right)$ of equation (5) has in most cases no influence on the end losses calculation, because $48 f^2$ is significantly larger than a^2. For this reason equation (4) is used in this publication.

Example 1:
A given collector has a focal length of 0.5 m and a length of 5 m. The angle of incidence is assumed to 45°, so the $IAM_{endloss}$ is calculated to:

$$IAM_{endloss} = 1 - 5 \cdot \frac{\tan 45}{50} = 0{,}92 \qquad (5)$$

Resulting from formula (4): The smaller the f/L ratio, the smaller are the end losses. This context is shown in Figure 7 for different f/L ratios.

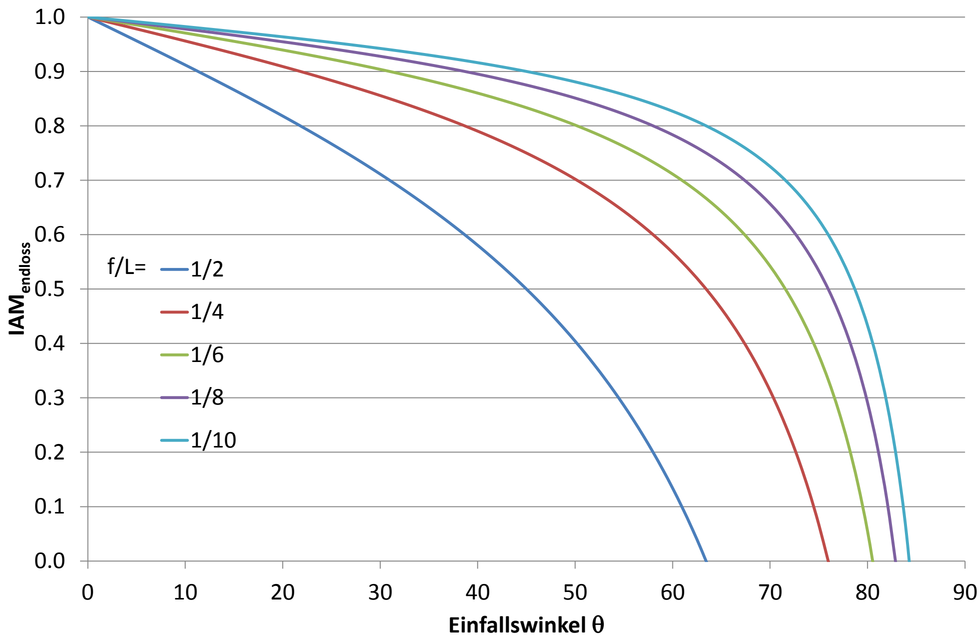

Figure 7: $IAM_{endloss}$ for different f/L ratios

End losses have different negative impacts on the efficiency of a collector. The Intercept factor decreases due to end losses which leads to a decrease of the optical efficiency. Another point is the usage of the aperture area. The non-illuminated part of the absorber tube reduces the efficient usage of the aperture area. Furthermore the non-illuminated part leads to an inhomogeneous heat flux along the absorber tube (Muthusivagami, 2011).

If there are several linear concentrating collectors in a row, a part of the end losses can be compensated. Thus the reflected solar radiation at the end of one collector, reaches the absorber of the next collector in the row. These effects are called end wins (Figure 8). The length of the illuminated absorber tube of the next collector can be calculated with formula (5) (Larcher, 2012).

$$l_{win} = f \cdot \tan\theta - d_D \qquad (5)$$

With

d_D = distance between the linear concentrating collectors

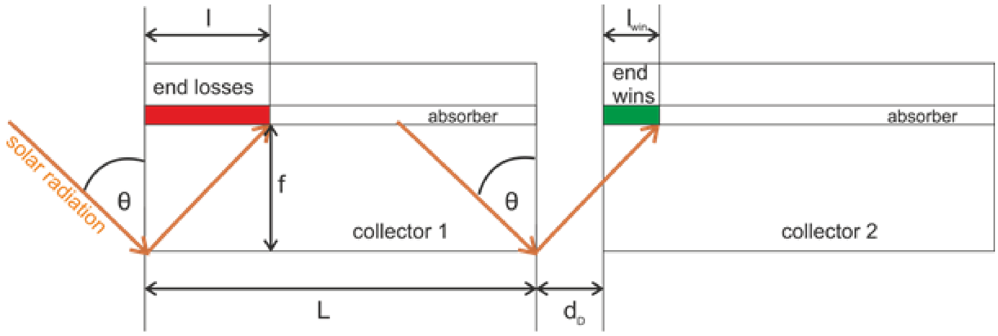

Figure 8: Geometric sketch of two parabolic trough collectors

Example 2:
For a focal length of 0.5 m, a distance of 0.3 m between the collectors and an angle of incidence of 45°, l_{win} is calculated to:

$$l_{win} = 0.5 \tan 45 - 0.3 = 0.2\, m$$

The not illuminated length of the absorber is calculated to:

$$l = 0.5 \cdot \tan 45 = 0.5\, m$$

Thus results an $IAM_{endloss}$:

$$IAM_{endloss} = 1 - \frac{l - l_{win}}{L} = 1 - \frac{0.5 - 0.2}{5} = 0{,}94$$

This means that for the second collector in a row the end losses are 6% on the same boundary conditions like in example 1. In example 1 the end losses are 8%.

References

Beckmann, William A. und Duffie, John A. 2006. *Solar Engineering of Thermal Processes.* s.l. : John Wiley & Sons, 2006. ISBN-13: 978-0471698678.

Larcher, Marco. 2012. *Ergebnisse von Messungen an einem 4m Segment des Parabolrinnenkollektors Poly Trough 1200.* [Hrsg.] Institut für Solartechnik SPF. 2012.

Mertins, Max. 2009. *Technische und wirtschaftliche Analyse von horizontalen Fresnel-Kollektoren.* Fakultät für Maschinenbau, Universität Karlsruhe. 2009. Dissertation.

Muthusivagami, R. M. 2011. *The Impact Of End Effects In Parabolic Trough Collector Pilot Set-Ups.* SSN Research Centre, Rajiv Gandhi Salai (OMR). 2011.

Patnode, Angela M. 2006. *Simulation and Performance Evaluation of Parabolic Trough Solar Power Plants.* University of Wisconsin-Madison. 2006. Masterarbeit.

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7 Text proposals for standard revision

This section summarises the text proposals for the revision of the Standard EN 12975-2 based on the findings described above and the corresponding discussions within work package 2 (WP2) of the QAiST project.

7.1 Terms and definitions

Enric Mateu Serrats (emateu@cener.com)

To define special terms applying for tracking and concentrating collectors which have not been covered so far by the EN ISO 9488 and the EN 12975 respectively a chapter called Terms and definition (see below) was included into the draft of the new standard.

3 Terms and definitions

For the purpose of this document, the terms and definitions given in EN ISO 9488 and the following ones apply.

3.1
acceptance angle
angular zone within which radiation is accepted by the receiver of a concentrating collector

NOTE 1 Radiation is said to be accepted because radiation incident within this angle reaches the absorber after passing through the aperture.

NOTE 2 See also field-of-view angle from ISO 9488 4.8. In this case, it applies not only to pyrheliometers but also to concentrating collectors.

3.2
cleanliness factor
ratio of optical efficiency in certain dirty conditions and the optical efficiency with the same optical element in unsoiled, clean condition. This factor can be applied to single components (reflector, receiver), or to the whole collector

3.3
collector rotation axis or tracking axis
pivot axis of a line-focus collector, in most cases parallel to the focal line {concentrating collector}

3.4
concentrator
part of the concentrating collector which directs radiation onto the receiver

3.5
concentrator axis
symmetry line orthogonal to the collector aperture normal in line-focus collector

3.6
cosine loss
loss given by the cosine of the angle of incidence due to the fact that the projected collector area visible from the Sun's direction is smaller than the collector aperture

3.7
end effects
loss of collected energy at the ends of the linear absorber in line-focus collectors, when the direct solar rays incident on the collector make a non-zero angle with respect to a plane perpendicular to the axis of the collector

3.8
incident angle modifier
ratio of the efficiency at off normal angles to the efficiency at normal incidence

3.9
intercept factor
fraction of reflected radiation which is intercepted by the receiver, (also capture fraction) {concentrating collector}

3.10
longitudinal angle of incidence
Angle between collector aperture normal and incident sun beam projected into the longitudinal plane.

NOTE not applicable to point-focus collectors and central receivers.

3.11
longitudinal plane
plane defined by the normal to the collector aperture and the concentrator axis (or the largest symmetry line for flat biaxial geometries)

3.12
maximum operating temperature
maximum temperature reached during collector or system normal operation, usually stated by the manufacturer {concentrating collector}

3.13
minimum acceptance angle
smallest angle of incidence for which the incident angle modifier is less than 0.7

3.14
module
smallest unit that would function as a solar energy collection device

3.15
nominal collector power
collector output thermal power, which can be achieved at design irradiance, normal incidence of solar radiation and design operation temperature

3.16
near-normal incidence
angular range from exact normal incidence within which the deviations in thermal performance measured at ambient temperature do not exceed 62 %, such that the errors caused by testing at angles other than exact normal incidence cannot be distinguished from errors caused by other inaccuracies (that is, instrumentation errors, etc.)

3.17
non concentrating collector
solar collector without any reflector, lens or other optical element to redirect and concentrate solar irradiance

3.18
no-flow condition
condition that occurs when the heat transfer fluid does not flow through the collector array, due to shut-down or malfunction, and the collector is exposed to the same solar irradiance as under normal operating conditions

3.19
optical axis
symmetry line orthogonal to focal line and aperture plane in line-focus collectors

3.20
outgassing
process in which a solid material releases gases when it is exposed to elevated temperatures and/or reduced pressure

3.21
optical efficiency or zero loss efficiency
theoretical efficiency of the collector without thermal losses

3.22
passive
operating condition where no human or mechanical intervention is required for operation as intended {concentrating collector}

3.23

quasi-dynamic test

determination of the optical efficiency and the heat loss factors of the collector from a relatively short testing period, with no requirement for steady state climatic conditions. Correction terms are introduced for beam and diffuse incidence angle modifiers, thermal capacitance, wind speed and sky temperature

3.24

reconcentrator

Reflectors used near the receiver for the purpose of increasing the concentration of sunlight on the receiver {Concentrating collector}

3.25

reflector or reflective surface

surface intended for the primary function of reflecting radiant energy {Concentrating collector}

NOTE It includes also the optional reconcentrator.

3.26

rim angle

maximum angle between the normal to the aperture plane and the line connecting the focus and the edge of the reflector in a cross section {Concentrating collector}

NOTE This definition is not applicable to an array of heliostats with central receiver

3.27

specular reflectance

reflectance measured within an acceptance angle of 25 mrad

3.28

thermal performance

Instantaneous thermal efficiency

3.29

transversal angle of incidence

angle between collector aperture normal and incident sun beam projected into the transversal plane

NOTE Not applicable to point-focus collectors and central receivers.

3.30

transversal plane

plane defined by the normal to the collector aperture and the line orthogonal to the concentrator axis (or the shortest symmetry line for flat biaxial geometries)

3.31
trigger or safety activation temperature
temperature value at which the safety controls are activated for fail safe operating condition {Concentrating collector}

7.2 Test method and procedure

Stephan Fischer (fischer@itw.uni-stuttgart.de)

In order to adapt the existing test method and procedure within EN 12975 to be used for tracking and concentrating collectors following paragraphs within chapter 6 of the current Standard have been modified or added as described below.

6 Thermal performance testing of fluid heating collectors

The thermal performance of glazed solar collectors shall be tested according to either 6.1, 6.2, 6.3 or 6.4.

…

The thermal performance of concentrating collectors shall be tested according 6.4.

Clause 6.1 may be used if a distinction between beam and diffuse irradiance is taken into account. However, in this case the requirements documented in clause 6.4 related to concentrating collectors (including equation 58) shall be followed.

6.4 Glazed and unglazed solar collectors under quasi-dynamic conditions

6.4.1 Collector mounting and location

6.4.1.1 General

Collectors shall be located and mounted in accordance with 6.1.1.1. Tracking concentrating collectors shall be tested using the tracking device of the manufacturer.

6.4.1.2 Collector mounting

Glazed collectors shall conform to 6.1.1.2 and unglazed collectors shall conform to 6.3.1.2. Tracking concentrating collectors shall be mounted in a way that enables performance testing up to incidence angles of 60°.

Note: For linear tracking collectors like parabolic trough collectors this can be easily achieved with an east-west orientation which enables testing of the incidence angle modifier for all angles within one day.

6.4.1.4 Collector orientation outdoors

NOTE The azimuthal deviation of collector (or pyranometer) from due south, should be taken into account when calculating the angle of incidence of solar radiation onto the collector aperture. Larger deviations from south may be acceptable, but will lead to a non-symmetrical angular distribution of beam radiation in Figure 15. This may lead to slightly biased incidence angle dependence of the collector. The actual incidence angle should be calculated with a standard uncertainty better than $\pm 1°$.

In case of non-imaging stationary collectors as CPCs, they should be mounted so that the beam radiation from the sun falls within the angular acceptance range of the design.

6.4.2.1.1.Pyranometer

Pyranometers shall conform to 6.1.2.1.1 with the following exception: sub clause 6.1.2.1.1.5is not applicable. In case of concentrating collectors the direct normal incidence (DNI) shall be measured with a pyrheliometer on its own tracking system. Beam and diffuse irradiance shall be calculated by:

$G_b = DNI * \cos\theta$

$G_d = G - G_b$

6.4.2.5.3 Mounting of sensors

…

In windy locations, the wind speed measurement shall be made near to the collector at the mid height of the collector. The sensor shall not be shielded from the wind and it shall not cast a shadow on the collector during test periods.

In case of concentrating collectors the following rules apply:

1. *Concentrating collectors without transparent cover and a concentration ration of C < 10 should be treated as uncovered collectors.*
2. *Concentrating collectors with transparent cover and with a concentration ratio of C< 3 should be treated as non-concentrating collectors.*

3. *For concentrating collectors with a transparent cover and a concentration ratio of C > 3 wind speed dependency can be neglected.*

For evacuated concentrating collectors wind speed dependency can be neglected independent of the concentration ratio C.

6.4.4.2 Preconditioning of the collector

The collector shall be preconditioned in accordance with 6.1.4.2. Concentrating collectors having a high concentration ratio may be exempt from this procedure, on request by the manufacturer,

6.4.4.3 Test conditions

…

NOTE For concentrating collectors, follow rules as given in 6.4.2.5.3.

…

6.4.4.8.3 Use of the collector Model for different collector types

The collector model as described in 6.4.4.8.2 should cover most collector designs available on the market, except ICS collectors. If the full collector model should be applied for a certain type of collector (or collector design) or not, will in general be given by the result of the parameter identification, but for all types of collectors, the use of $\eta_{0,b,en}$, $K_{\theta b}(\theta)$, $K_{\theta d}$ and the coefficients c_1, c_2, and c_5 are mandatory and they should be identified.

NOTE 1 For sun tracking, high concentrating collectors the inclusion of $K_{\theta d}$ may not always be significant and should therefore be determined by the T-ratio of the parameter identification as given below.

Then $K_{\theta d} = 0$ should be used in Equation (57) and the parameter identification should be repeated.

…

Not yet included in the draft of EN ISO 9806 is the requirement that all performance testing of concentrating and tracking collectors need to be carried out with the tracking system supplied by the manufacturer.

7.3 Properties of water

Carsten Lampe (c.lampe@isfh.de)

In order to give correct properties of water for temperatures above 100 °C and for pressures up to 12 bar the following sections have been included into the current draft.

J.2 Density of water (at 1 to 12 bar) in kg/m³

The equation given in J.1 is valid for the temperature range $(0 \le \vartheta \le 99{,}5°C)$ *and an extrapolation to higher temperatures leads to a significant deviation. The following equation results in a fit of data given for water at 1 bar*[2] $(0 \le \vartheta \le 99{,}6°C)$ *and at 12 bars*[3] $(100 \le \vartheta \le 185°C)$*. The water is assumed to be in liquid phase.*

$$\rho(\vartheta) = a_0 + a_1\vartheta + a_2\vartheta^2 + a_3\vartheta^3 + a_4\vartheta^4 + a_5\vartheta^5$$

$$(0 \le \vartheta \le 185°C)$$

with

$a_0 =$ *999,85*

$a_1 =$ *5,332* 10^{-2}

$a_2 =$ *-7,564* 10^{-3}

$a_3 =$ *4,323* 10^{-5}

$a_4 =$ *-1,673* 10^{-7}

$a_5 =$ *2,447* 10^{-10}

The deviation of the polynomial to the values from those references is always smaller than 0,03% (compared to VDI $(0 \le \vartheta \le 99{,}6°C)$*) or 0,12% (compared to IAPWS* $(0 \le \vartheta \le 185°C)$*). The extrapolation to higher temperatures does not lead to such a high deviation as that of J.1 but in case of need it shall be checked or another equation shall be used.*

---

2 Verein Deutscher Ingenieure (editor): VDI Wärmeatlas, 10. ed,; Springer-Verlag Berlin, 2006

3 Wagner et al.: The IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam; ASME, Journal of Engineering for Gas Turbines and Power, Volume 122, 2000

J.4 Specific heat capacity of water (at 1 to 12 bar) in kJ/(kg K)

The equation given in J.3 is valid for the temperature range $(0 \le \vartheta \le 99{,}5°C)$ *and an extrapolation to higher temperatures leads to a significant deviation. The following equation results in a fit of data given for water at 1 bar*[4] $(0 \le \vartheta \le 99{,}6°C)$ *and at 12 bars*[5] $(100 \le \vartheta \le 185°C)$*. The water is assumed to be in liquid phase.*

$$c_p(\vartheta) = a_0 + a_1\vartheta + a_2\vartheta^2 + a_3\vartheta^3 + a_4\vartheta^4 + a_5\vartheta^5 + a_6\vartheta^6$$

$$(0 \le \vartheta \le 185°C)$$

a_0 = $4{,}2184$

a_1 = $-2{,}8218 \; 10^{-3}$

a_2 = $7{,}3478 \; 10^{-5}$

a_3 = $-9{,}4712 \; 10^{-7}$

a_4 = $7{,}2869 \; 10^{-9}$

a_5 = $-2{,}8098 \; 10^{-11}$

a_6 = $4{,}4008 \; 10^{-14}$

The deviation of the polynomial to the values from those references is always smaller than 0,04% (compared to VDI $(0 \le \vartheta \le 99{,}6°C)$*) or 0,14% (compared to IAPWS* $(0 \le \vartheta \le 185°C)$*). The extrapolation to higher temperatures does not lead to such a high deviation as that of L3 but in case of need it shall be checked or another equation shall be used.*

4 Verein Deutscher Ingenieure (editor): VDI Wärmeatlas, 10. ed,; Springer-Verlag Berlin, 2006

5 Wagner et al.: The IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam; ASME, Journal of Engineering for Gas Turbines and Power, Volume 122, 2000

8 Proposals for future work

During the work related to performance testing of concentrating and tracking collectors new issues came up which are relevant for solar thermal industry as well as for the users of solar thermal collectors.

This section lists and describes the most relevant issues to pave the way to future work items.

8.1 Cooperation between stakeholders of different technologies

Enric Mateu Serrats (ematеu@cener.com)

Nowadays, concentrating/tracking collectors and their components do not have specific standards for their performance and durability characterization. Some parallel standardization activities have been established up to now. These activities involve different regional and international standardization committees due to the wide spectrum of concentrating solar thermal collector applications.

Low to medium temperature applications:

The path to a unique international standard for solar thermal collectors started in 2009 when the CEN/TC312 WG1 initiated the revision of the EN 12975 standard after the approval of the QAIST project. At the same time, IEA-SHC Task 43 started its activities in order to disseminate and built consensus around the EN 12975 revision activities on a global level. Due to the lack of activity on the ISO 9806 revision, ISO/TC180 decided to closely follow the EN 12975 revision process, and in August 2011 ISO/TC180 determined that the ISO 9806 standard will be revised and based on the EN 12975 revision. The CEN/TC312 WG1 decided to postpone the public input portion of the EN 12975 revision in order to catch up with the ISO 9806 revision process. In September 2011, it was decided that the EN ISO 9806 will be developed under the Vienna Agreement (VA) under CEN leadership by establishing joint working groups from CEN/TC312 and ISO/TC180 to develop a common international standard for solar thermal collectors. A further agreement was reached to create a multi-part standard on collector components and materials (taking China proposals into consideration), also to be conducted under VA with some parts lead by CEN and others by ISO:

- ISO lead – Part 1: Evacuated tube durability and performance
- ISO lead – Part 2: Heat pipes for evacuated tubes - Durability and performance
- CEN lead – Part 3: Durability of absorber surface, glazing, and insulation materials, in coordination with the developments of the new IEC/TC117 for CSP components like: receiver, reflector or tracking system which could be also included as new parts in the

near future, based on the CSP existing test methods described in the QAIST WP2 Topic report R2.4 Concentrating/tracking collector component characterization.

High temperature applications or concentrated solar power (CSP):

At the beginning of 2010 the Spanish Association for Standardization and Certification (AENOR) created a new subcommittee inside the electricity production technical committee (AEN/CTN206) to deal with standardization activities related with solar thermal electric plants. The aim of this subcommittee is to create a series of Spanish Standards (UNE) that will define procedures to qualify components (receiver tubes, tracking systems, reflectors, etc.), subsystems (solar field, thermal storage system and power block) and complete CSP plants. Within this subcommittee, three different working groups (WG) have been created concerned with different aspects of the CSP plant: the first working group deals with standardization aspects related to the solar field and the CSP plant as a whole; the second working group develops standardization procedures related to the components of solar thermal power plants; and the third working group is focused on the standardization of thermal storage systems for CSP applications.

Due to the lack of standardization in this field, the International Electrotechnical Commission (IEC) technical committeeTC117 for Solar Thermal Electric has been recently created and its work program was established during the kick-off meeting held on March 7th-8th 2012 in Madrid. During this meeting a close collaboration between the new IEC/TC117 and the ISO/TC180 was agreed having also in its scope the concentrating/ tracking collectors and their components.

Another common point between low/medium temperature and CSP applications is the new set of definitions developed within the QAIST project and already included in the ISO/DIS 9806 standard. The new set of parameter definitions has also been agreed within the IEA-SHC Task 43, the CEN TC312 WG1, the solar thermal electric plants subcommittee from AENOR (Spain) and revised by Jean-Marc Suter former convenor of the ISO TC180 WG1. The definitions are general enough to cover the different collector technologies allowing a fair comparison of their thermal performance test results. Most of the definitions are dealing with concentrating collector terms are mainly applicable to line-focus collectors due to the difficulty of having broad definitions which also cover central receiver systems (out of the scope of testing standards). This set of definitions will be included in a near future in the next revision of the ISO 9488 Solar Energy vocabulary.

The anticipated date of availability for the new EN ISO 9806 standard will be on the second semester of 2013. This international standard will pave the way towards a global certification scheme for solar thermal collectors.

8.2 Components

Stephan Fischer (fischer@itw.uni-stuttgart.de)

Methods how to characterise important components of tracking and concentrating collectors like reflector material, receivers and tracking systems is described in QAiST report *R2.4 Topic report for WP2 Concentrating/tracking collector component characterization*. Nevertheless additional effort is needed to convert the methods into a recognized standard.

8.3 In-situ measurements

Franz Helminger (Franz.Helminger@ait.ac.at)

More and more collectors are built in sizes which cannot be tested in laboratory scale (parabolic troughs, linear Fresnel collector fields, collectors with linear mirrors, fixed mirror concentrating collectors). Such collectors are used in innovative concepts for solar heat in industrial processes and power plants and will bring solar heating one step closer to 2020-targets. To ensure the energy output, the power and temperature levels of such innovative concepts investors, manufacturers, planers and funding authorities are interested in independent measurements (third party measurements).

Basically performance measurements in such collector applications can be done according EN 12975-2. The method with quasi-dynamic conditions provides a physical model which covers most of the requirements and conditions of such collector applications, but some work need to be done to:

- Improve and adapt method to special needs of collector fields and innovative concepts (end losses, area definitions, tracking accuracy, incident angle modifiers, temperature levels)
- Gain experience
- Ensure comparability of method and results
- Dissemination of methods to interested parties

Durability tests for innovative collector concepts may differ to the standardized tests according to EN 12975-2 (e.g. active/passive protection devices, non-flat shapes of covers and reflectors). The requirements and methods maybe need to be updated according to environmental impacts, regional requirements and additional requirements (e.g. corrosion, degradation by abrasion)

8.4 Round Robin testing up to 200 °C

Franz Helminger (Franz.Helminger@ait.ac.at)

Test results need to be accurate, reliable, repeatable and comparable. The round robin in QAiST showed that results of testing solar collectors and systems in laboratory scale are satisfying and comparable all over Europe. Even new test issues especially for mid temperature range face these benchmark. A round robin for performance measurements of innovative mid/high temperature collectors is one step to ensure the comparability and reliability of results of third party measurements. The processing of such a mid/high temperature round robin as well as the measurements itself will be a more complex challenge for all participants, especially the sizes and transportation of mid/high temperature collectors will be critical issues. The processing with an independent body like IfEP (Germany) was very helpful and should be continued. A procedure for a mid/high temperature round robin need to be developed and temperature levels and special heat transfer fluids need to be taken into account.

8.5 Phase change liquids

Stephan Fischer (fischer@itw.uni-stuttgart.de)

Industrial process heat is coming more and more in the focus of solar thermal industries. Saturated steam is a common and widespread medium to transfer heat in industrial processes. With concentrating and tracking collectors it is possible to produce the required steam for industrial processes. However up to now the phase change liquids like evaporating water and the resulting two-phase flow conditions are not covered by the current standard. In order to open this important field of solar thermal future work related to the performance modelling and testing with two-phase flow and saturated steam need to be carried out.

Annex 1: Working paper on impact of wind speed on concentrating collectors during performance measurement

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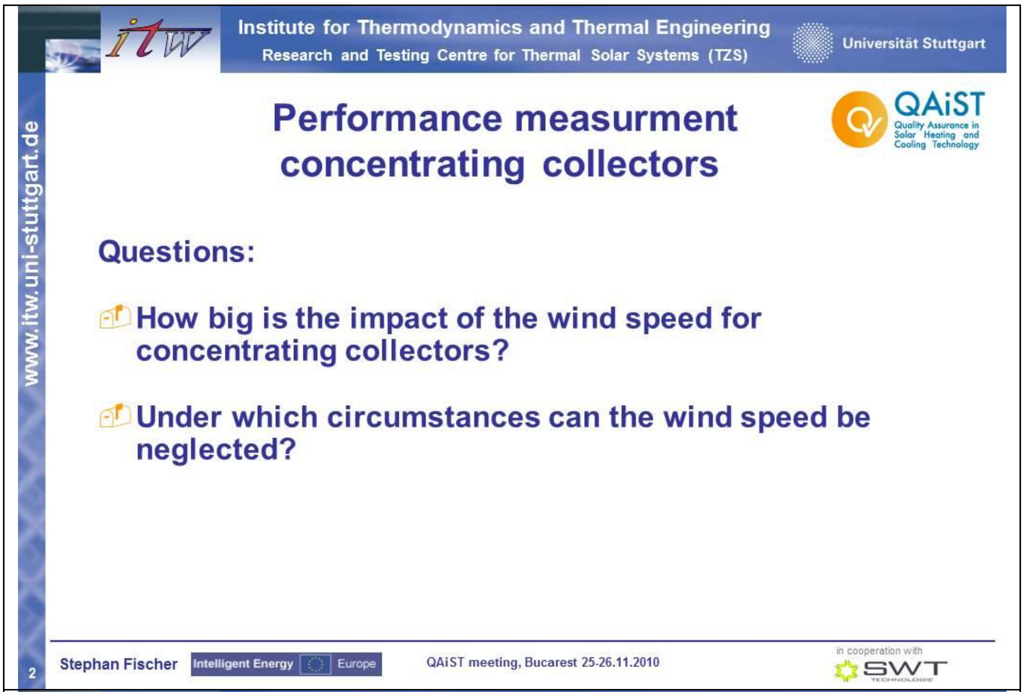

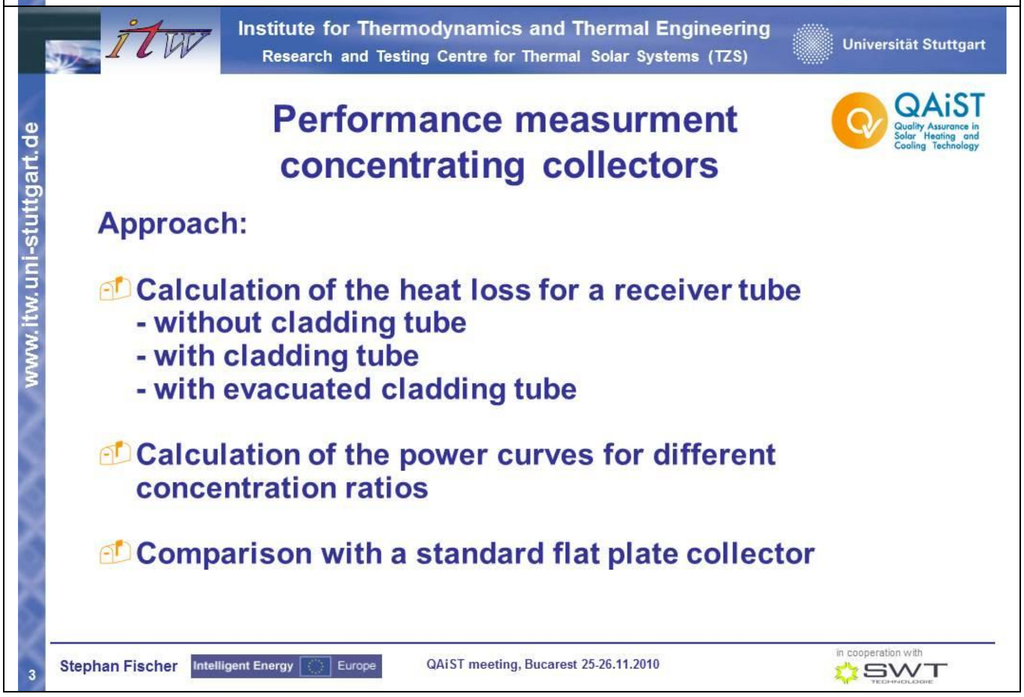

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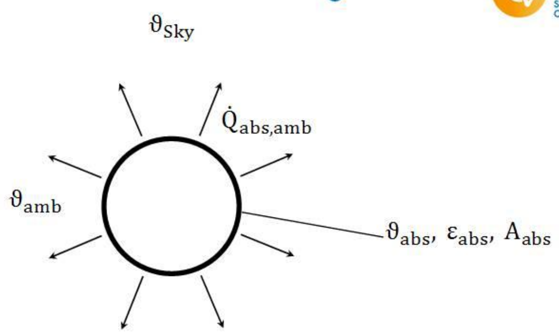
Heat Loss without cladding tube



$$\dot{Q}_{abs,amb} = \alpha_{abs,amb} A_{abs} (\vartheta_{abs} - \vartheta_{amb}) + \sigma \varepsilon_{abs} A_{abs} (T_{abs}^4 - T_{sky}^4)$$

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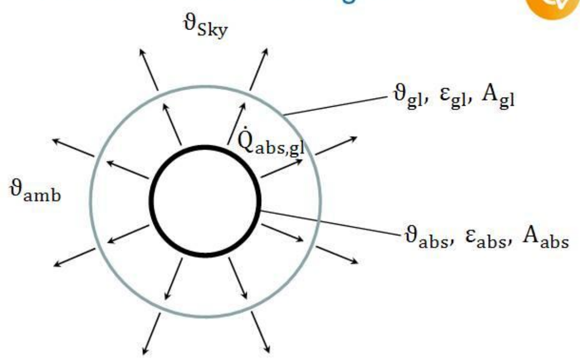
Heat Loss with cladding tube



$$\dot{Q}_{abs,gl} = \alpha_{abs,gl} A_{abs} (\vartheta_{abs} - \vartheta_{gl}) + \frac{\sigma \varepsilon_{abs} \varepsilon_{gl} A_{abs} \varphi_{abs,gl}}{1 - (1 - \varepsilon_{abs})(1 - \varepsilon_{gl}) \varphi_{abs,gl} \varphi_{gl,abs}} (T_{abs}^4 - T_{gl}^4)$$

$$\dot{Q}_{gl,amb} = \alpha_{gl,amb} A_{abs} (\vartheta_{gl} - \vartheta_{amb}) + \sigma \varepsilon_{gl} A_{gl} (T_{gl}^4 - T_{sky}^4)$$

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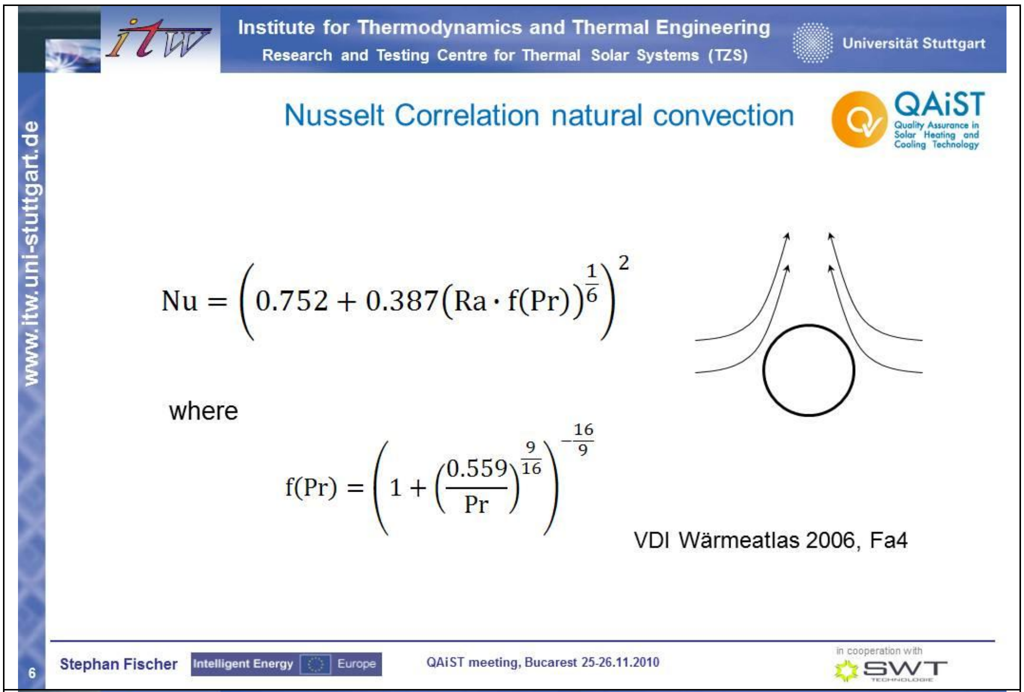
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Nusselt Correlation natural convection
$\mathrm{Nu} = \left(0.752 + 0.387\left(\mathrm{Ra}\cdot f(\mathrm{Pr})\right)^{\frac{1}{6}}\right)^2$
where
$f(\mathrm{Pr}) = \left(1 + \left(\frac{0.559}{\mathrm{Pr}}\right)^{\frac{9}{16}}\right)^{-\frac{16}{9}}$
VDI Wärmeatlas 2006, Fa4
6
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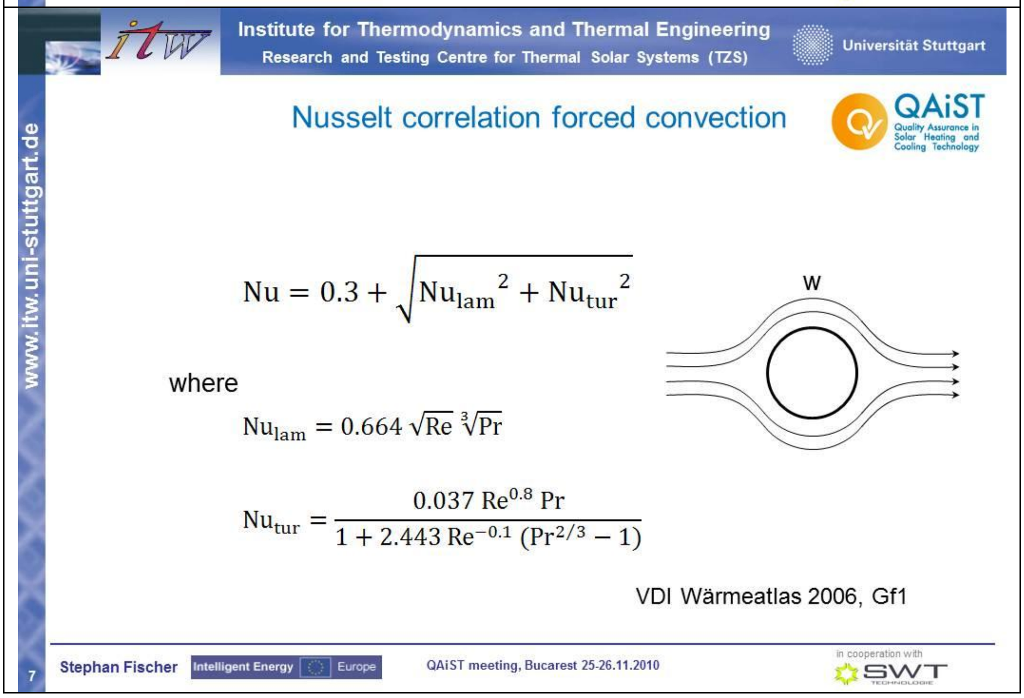
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Nusselt correlation forced convection
$\mathrm{Nu} = 0.3 + \sqrt{\mathrm{Nu_{lam}}^2 + \mathrm{Nu_{tur}}^2}$
w
where
$\mathrm{Nu_{lam}} = 0.664\,\sqrt{\mathrm{Re}}\,\sqrt[3]{\mathrm{Pr}}$
$\mathrm{Nu_{tur}} = \frac{0.037\,\mathrm{Re}^{0.8}\,\mathrm{Pr}}{1 + 2.443\,\mathrm{Re}^{-0.1}\,(\mathrm{Pr}^{2/3} - 1)}$
VDI Wärmeatlas 2006, Gf1
7
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Nusselt correlation for annulus

if $GrPr > 10^4$: $Nu = 0.2\,(GrPr)^{\frac{1}{4}}$

if $10^2 < GrPr < 10^4$:

$$Nu = 1 + 0.54 \cdot 10^{-4} GrPr + 1{,}482 \cdot 10^{-8} (GrPr)^2 + 1{,}021 \cdot 10^{-12} (GrPr)^3$$

if $GrPr < 10^2$: $Nu = 1$

Heat transfer coefficient in annulus

$$\alpha_{abs,gl} = \frac{Nu\lambda}{d_a} \frac{2}{\ln(D_i/d_a)}$$

Müller, Erhard 1999

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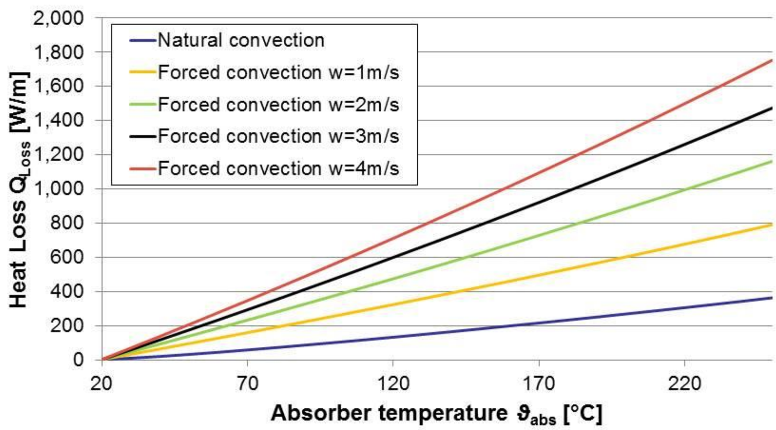
Heat Loss without cladding tube

Example: d_a = 47 mm, ϑ_{amb} = 20°C, ϑ_{sky} = 4°C, ε_{abs} = 0.1



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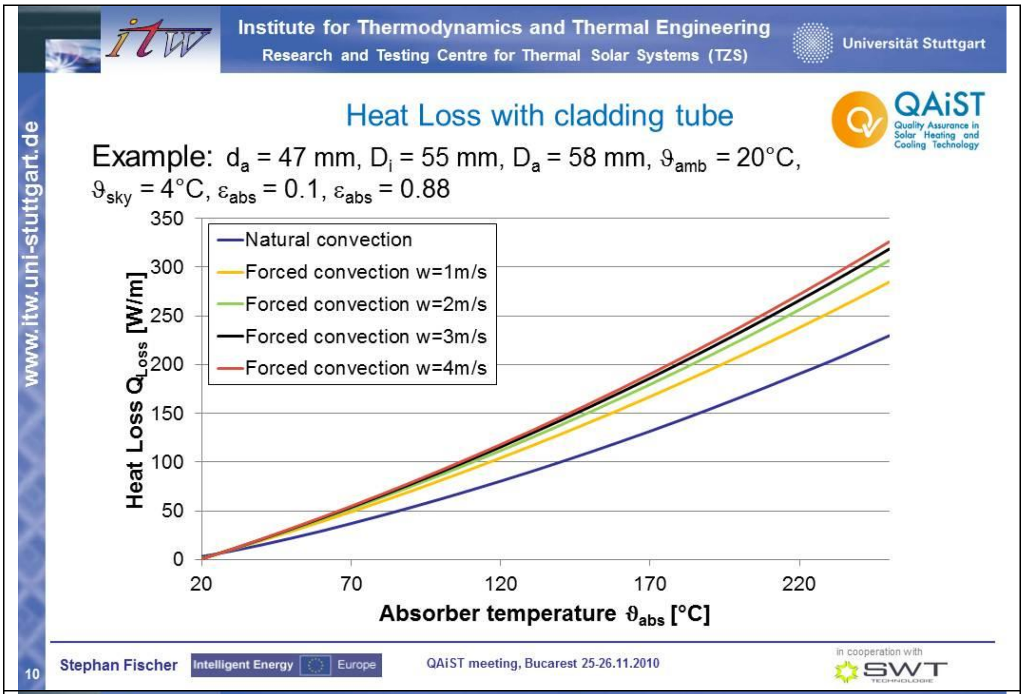

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Heat Loss with cladding tube
Example: d_a = 47 mm, D_i = 55 mm, D_a = 58 mm, ϑ_{amb} = 20°C, ϑ_{sky} = 4°C, ε_{abs} = 0.1, ε_{abs} = 0.88
Natural convection
Forced convection w=1m/s
Forced convection w=2m/s
Forced convection w=3m/s
Forced convection w=4m/s
Heat Loss Q_{Loss} [W/m]
Absorber temperature ϑ_{abs} [°C]
10
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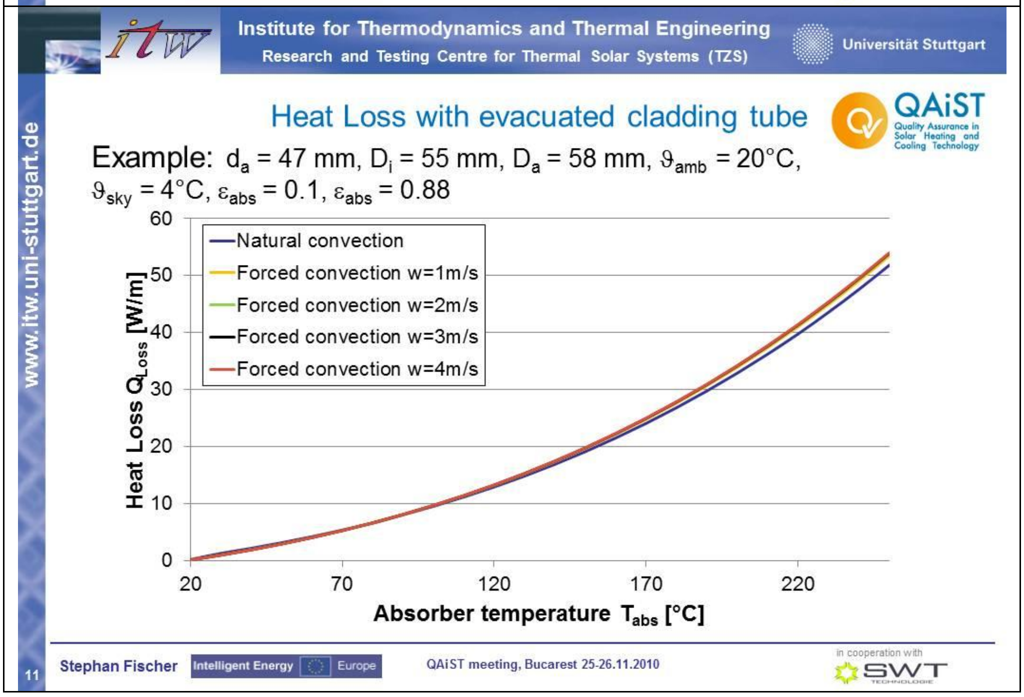

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Heat Loss with evacuated cladding tube
Example: d_a = 47 mm, D_i = 55 mm, D_a = 58 mm, ϑ_{amb} = 20°C, ϑ_{sky} = 4°C, ε_{abs} = 0.1, ε_{abs} = 0.88
Natural convection
Forced convection w=1m/s
Forced convection w=2m/s
Forced convection w=3m/s
Forced convection w=4m/s
Heat Loss Q_{Loss} [W/m]
Absorber temperature T_{abs} [°C]
11
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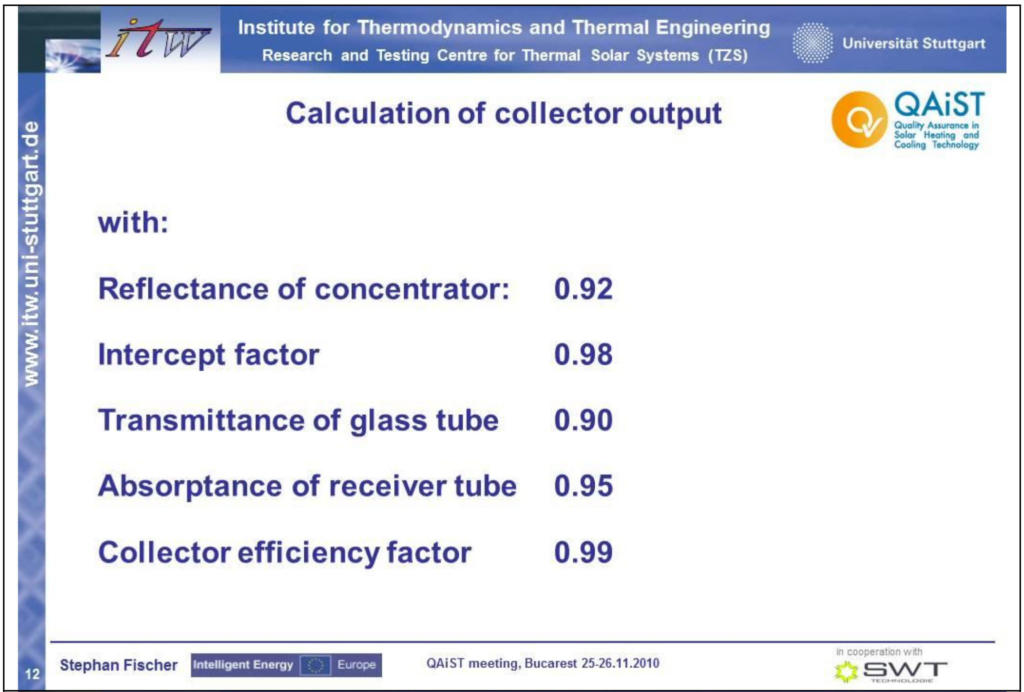
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Calculation of collector output
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with:
Reflectance of concentrator: 0.92
Intercept factor 0.98
Transmittance of glass tube 0.90
Absorptance of receiver tube 0.95
Collector efficiency factor 0.99
12
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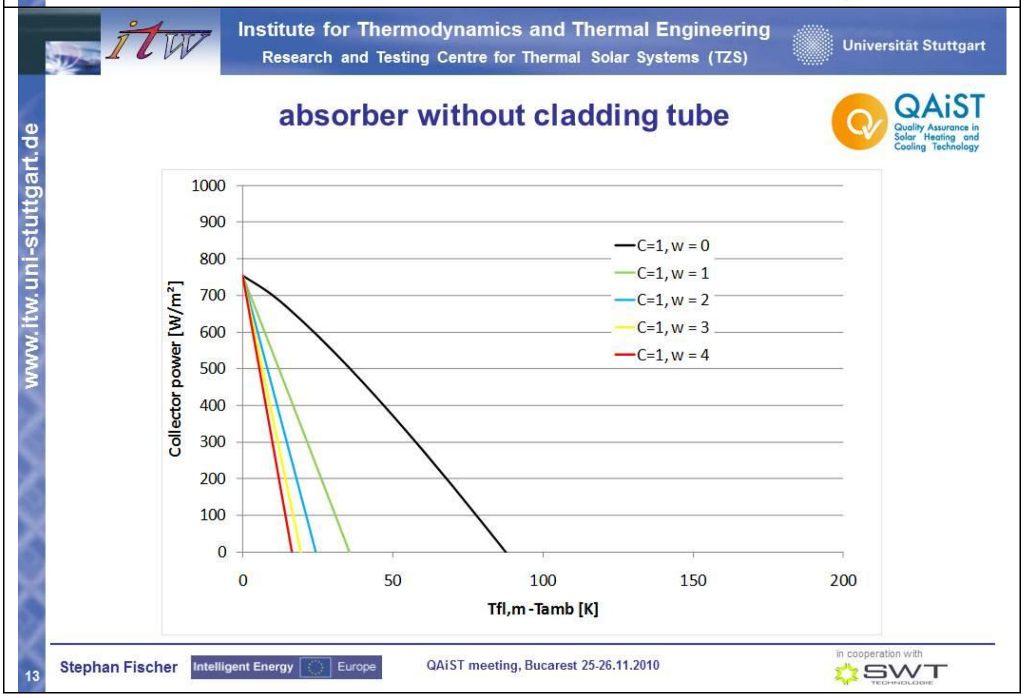
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absorber without cladding tube
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Collector power [W/m²]
1000
900
800
700
600
500
400
300
200
100
0
0
50
100
150
200
Tfl,m -Tamb [K]
C=1, w = 0
C=1, w = 1
C=1, w = 2
C=1, w = 3
C=1, w = 4
13
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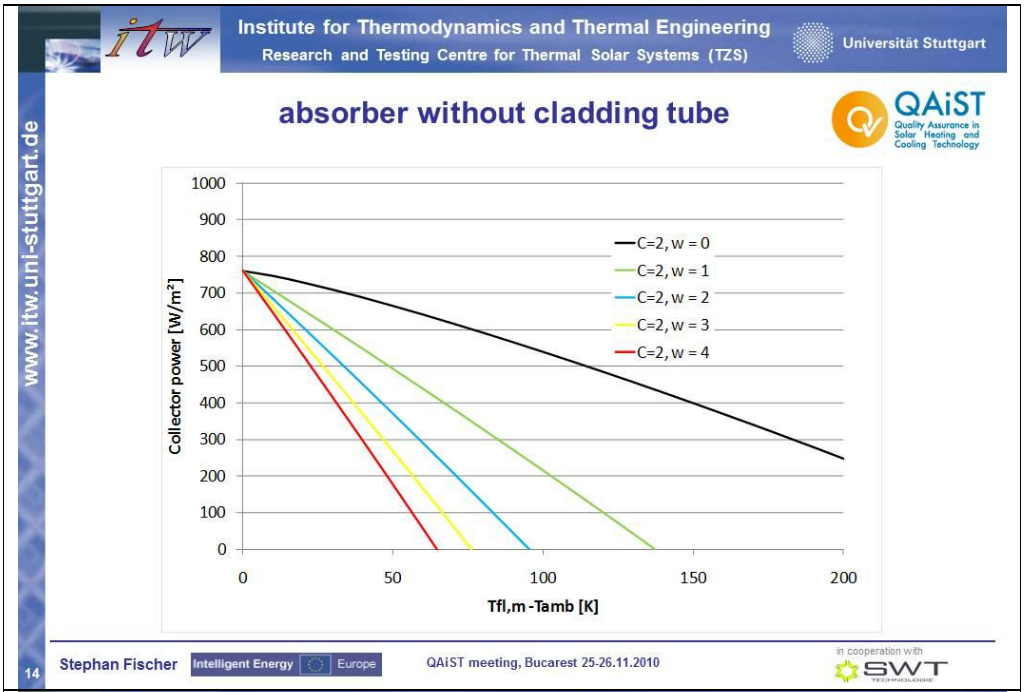

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absorber without cladding tube
QAiST
Quality Assurance in Solar Heating and Cooling Technology
Collector power [W/m²]
Tfl,m -Tamb [K]
C=2, w = 0
C=2, w = 1
C=2, w = 2
C=2, w = 3
C=2, w = 4
1000
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14
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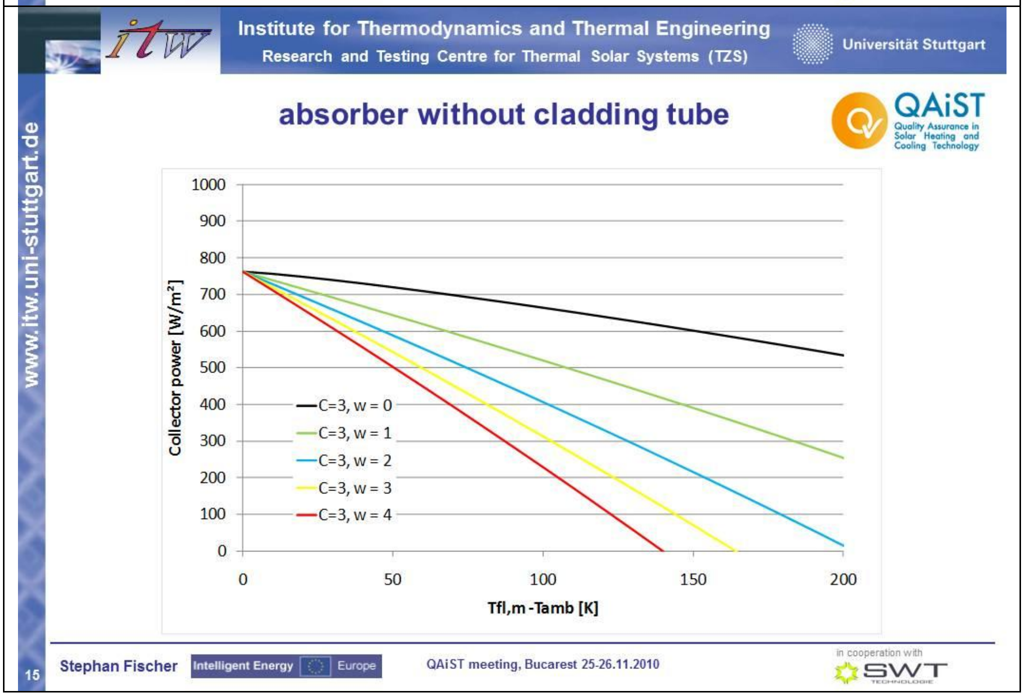

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Collector power [W/m²]
Tfl,m -Tamb [K]
C=3, w = 0
C=3, w = 1
C=3, w = 2
C=3, w = 3
C=3, w = 4
1000
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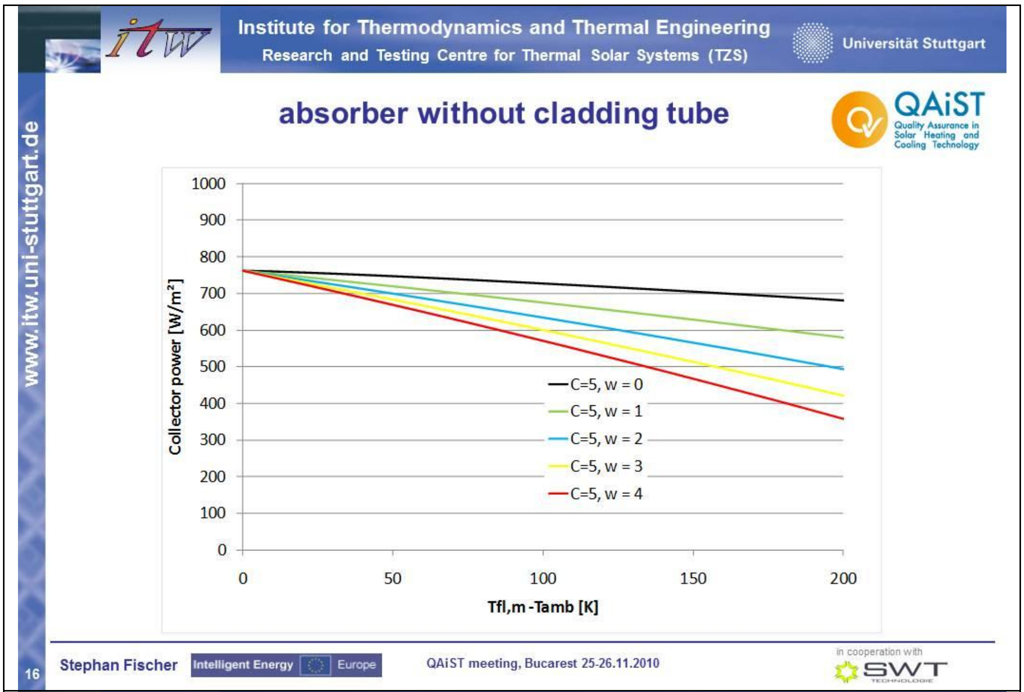
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absorber without cladding tube
Collector power [W/m²]
Tfl,m -Tamb [K]
C=5, w = 0
C=5, w = 1
C=5, w = 2
C=5, w = 3
C=5, w = 4
16
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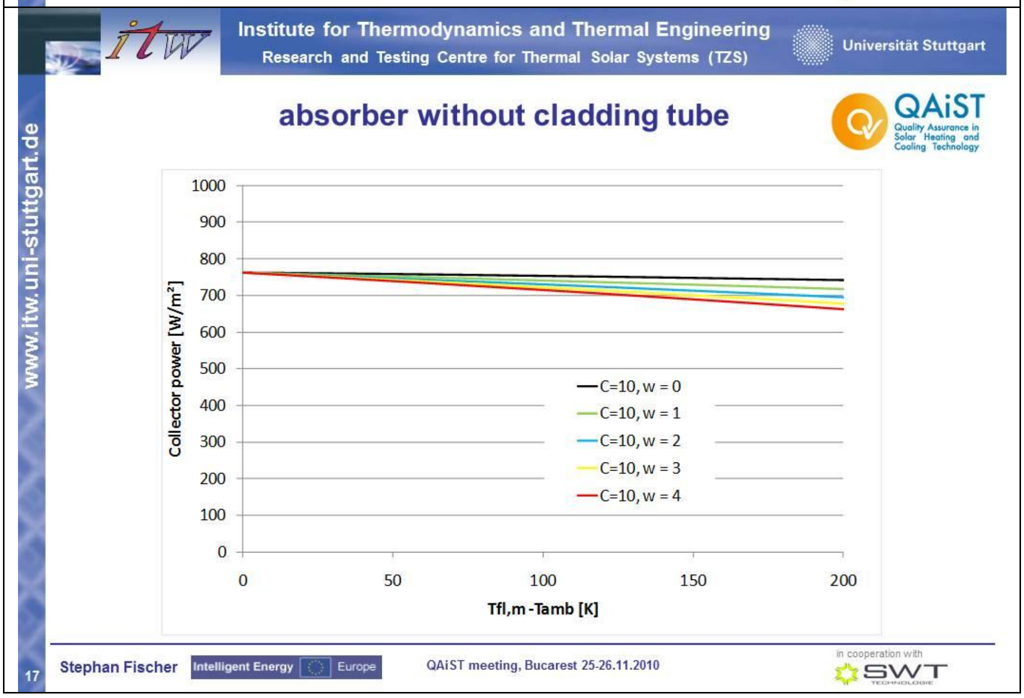
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absorber without cladding tube
Collector power [W/m²]
Tfl,m -Tamb [K]
C=10, w = 0
C=10, w = 1
C=10, w = 2
C=10, w = 3
C=10, w = 4
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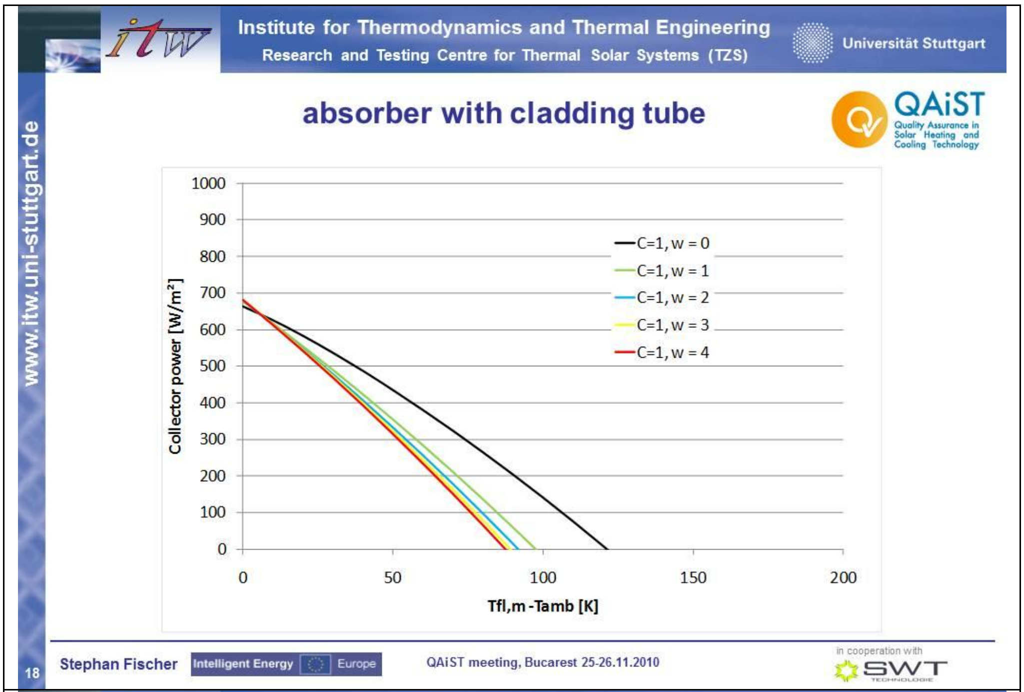
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absorber with cladding tube
Collector power [W/m²]
Tfl,m -Tamb [K]
C=1, w = 0
C=1, w = 1
C=1, w = 2
C=1, w = 3
C=1, w = 4
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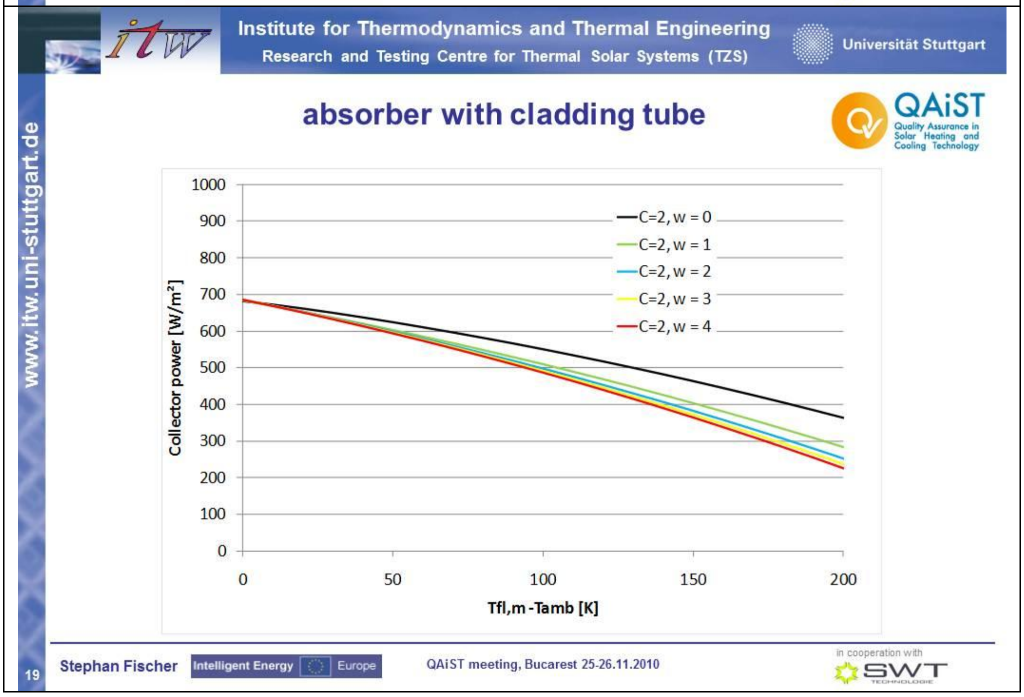
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absorber with cladding tube
Collector power [W/m²]
Tfl,m -Tamb [K]
C=2, w = 0
C=2, w = 1
C=2, w = 2
C=2, w = 3
C=2, w = 4
19
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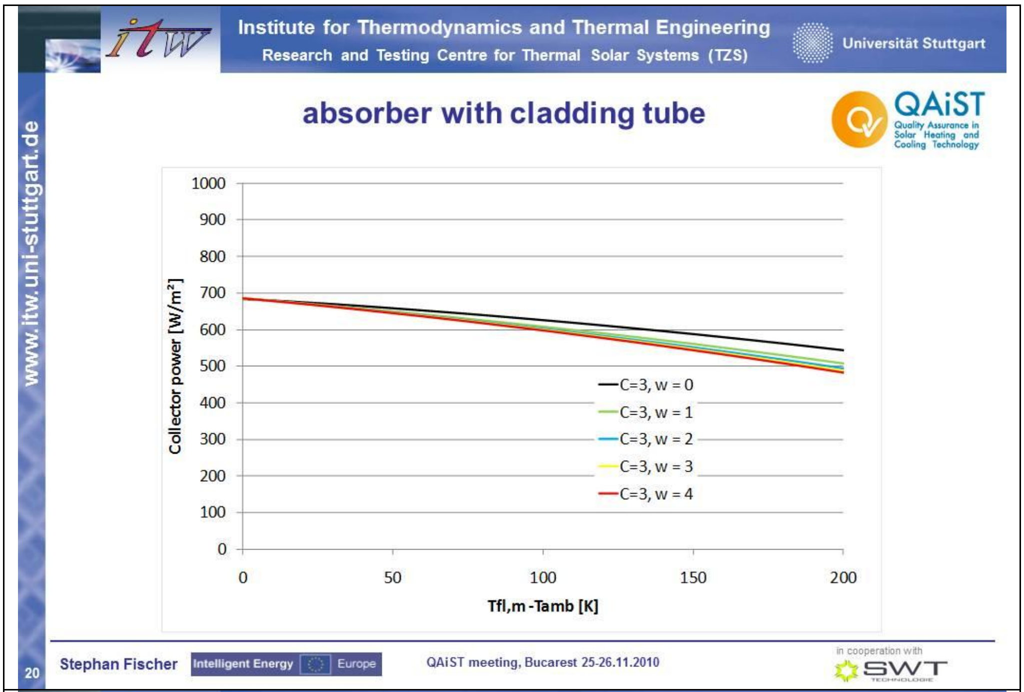
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absorber with cladding tube
Collector power [W/m²]
Tfl,m -Tamb [K]
C=3, w = 0
C=3, w = 1
C=3, w = 2
C=3, w = 3
C=3, w = 4
20
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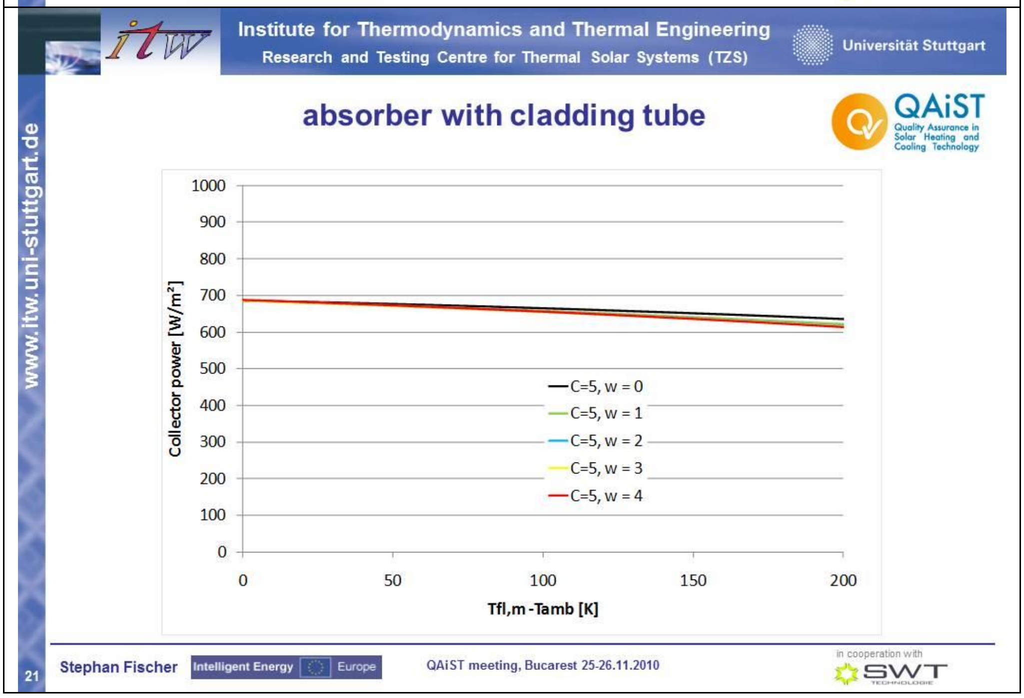
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absorber with cladding tube
Collector power [W/m²]
Tfl,m -Tamb [K]
C=5, w = 0
C=5, w = 1
C=5, w = 2
C=5, w = 3
C=5, w = 4
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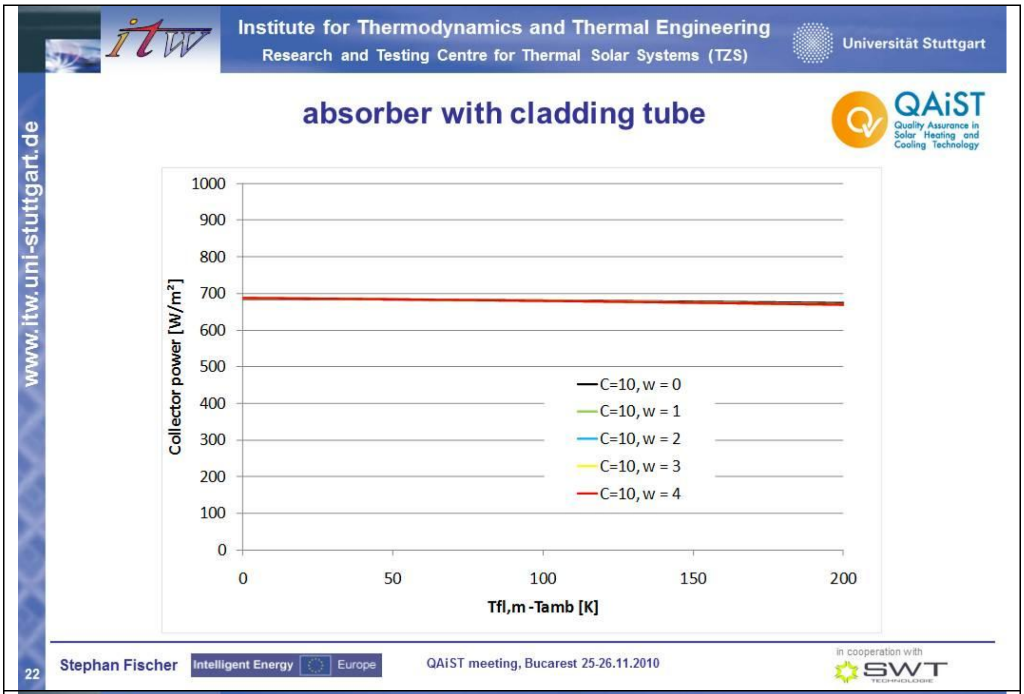
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absorber with cladding tube
Collector power [W/m²]
Tfl,m -Tamb [K]
C=10, w = 0
C=10, w = 1
C=10, w = 2
C=10, w = 3
C=10, w = 4
22
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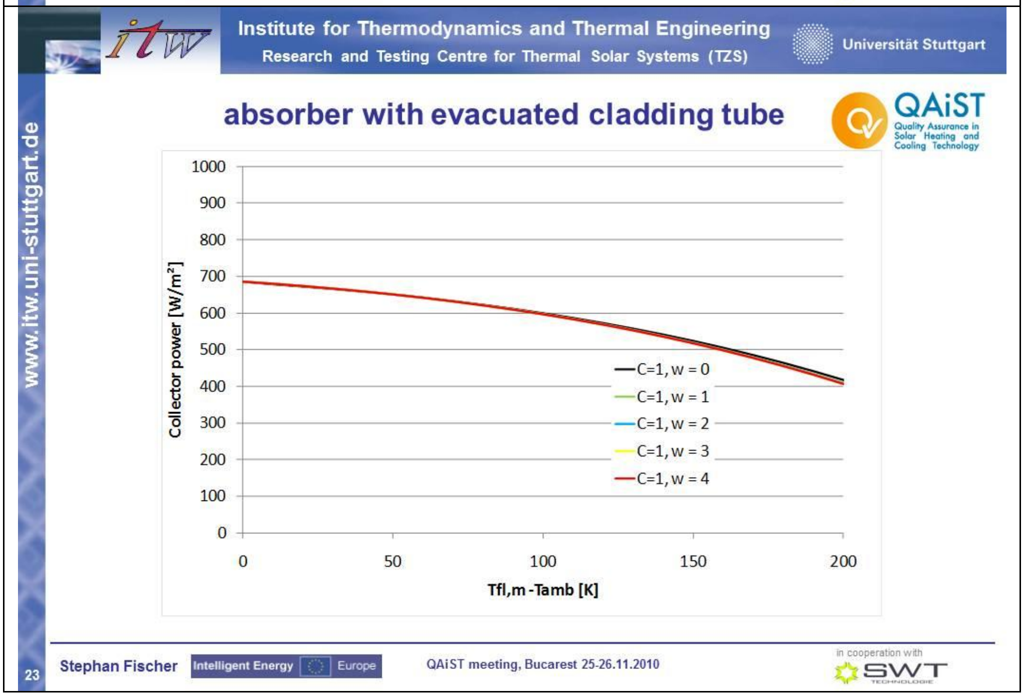
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absorber with evacuated cladding tube
Collector power [W/m²]
Tfl,m -Tamb [K]
C=1, w = 0
C=1, w = 1
C=1, w = 2
C=1, w = 3
C=1, w = 4
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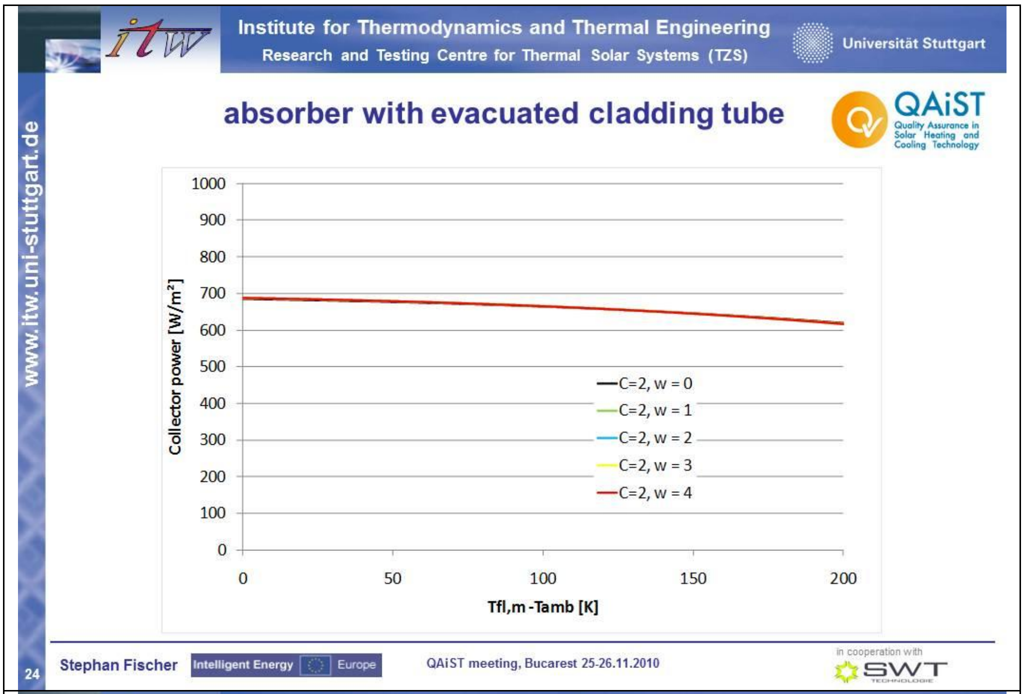
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absorber with evacuated cladding tube
Collector power [W/m²]
Tfl,m -Tamb [K]
C=2, w = 0
C=2, w = 1
C=2, w = 2
C=2, w = 3
C=2, w = 4
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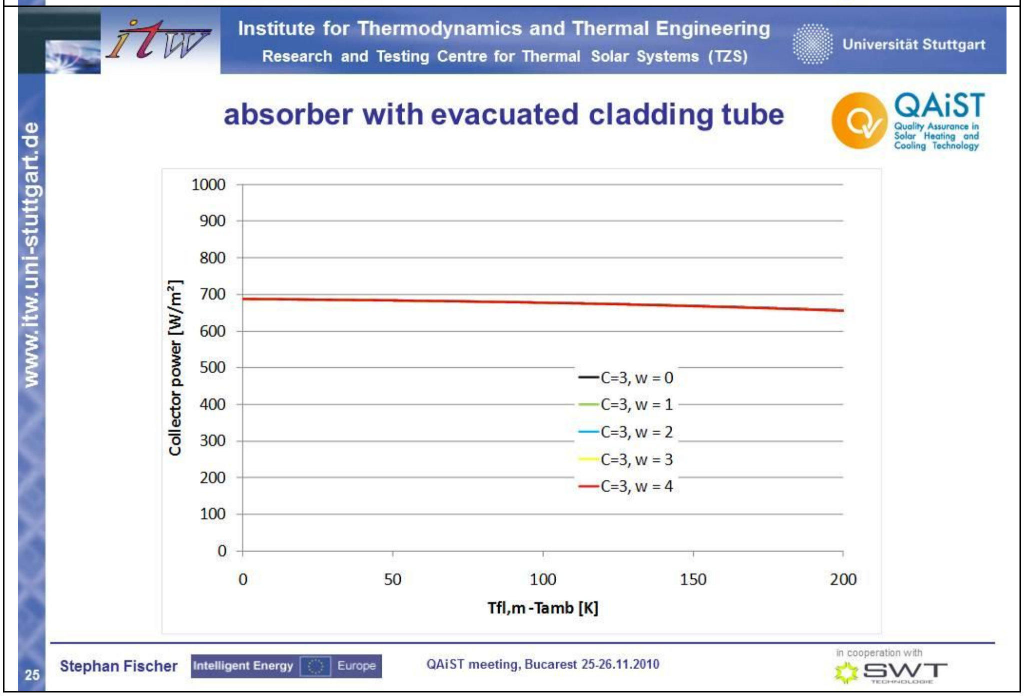
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absorber with evacuated cladding tube
Collector power [W/m²]
Tfl,m -Tamb [K]
C=3, w = 0
C=3, w = 1
C=3, w = 2
C=3, w = 3
C=3, w = 4
25
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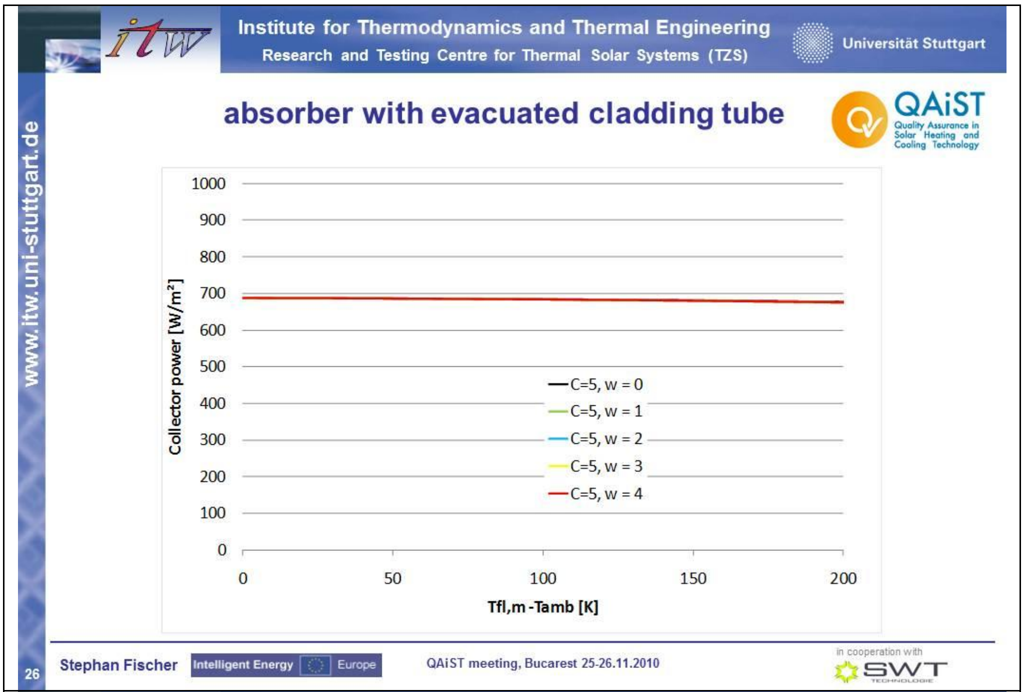
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absorber with evacuated cladding tube
Collector power [W/m²]
Tfl,m -Tamb [K]
C=5, w = 0
C=5, w = 1
C=5, w = 2
C=5, w = 3
C=5, w = 4
26
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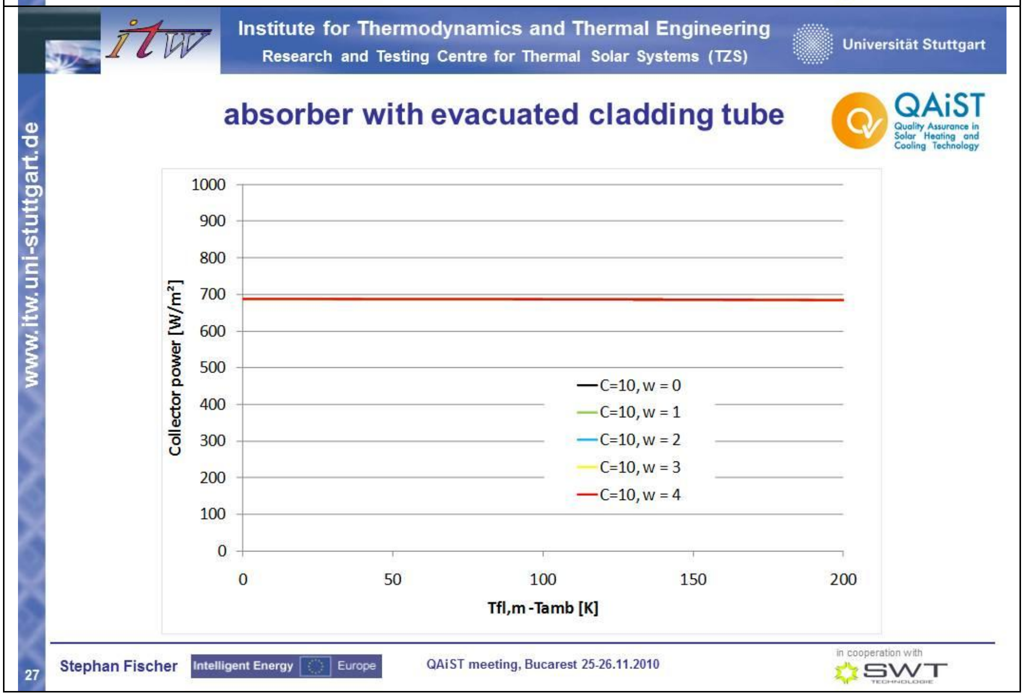
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Universität Stuttgart
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absorber with evacuated cladding tube
Collector power [W/m²]
Tfl,m -Tamb [K]
C=10, w = 0
C=10, w = 1
C=10, w = 2
C=10, w = 3
C=10, w = 4
27
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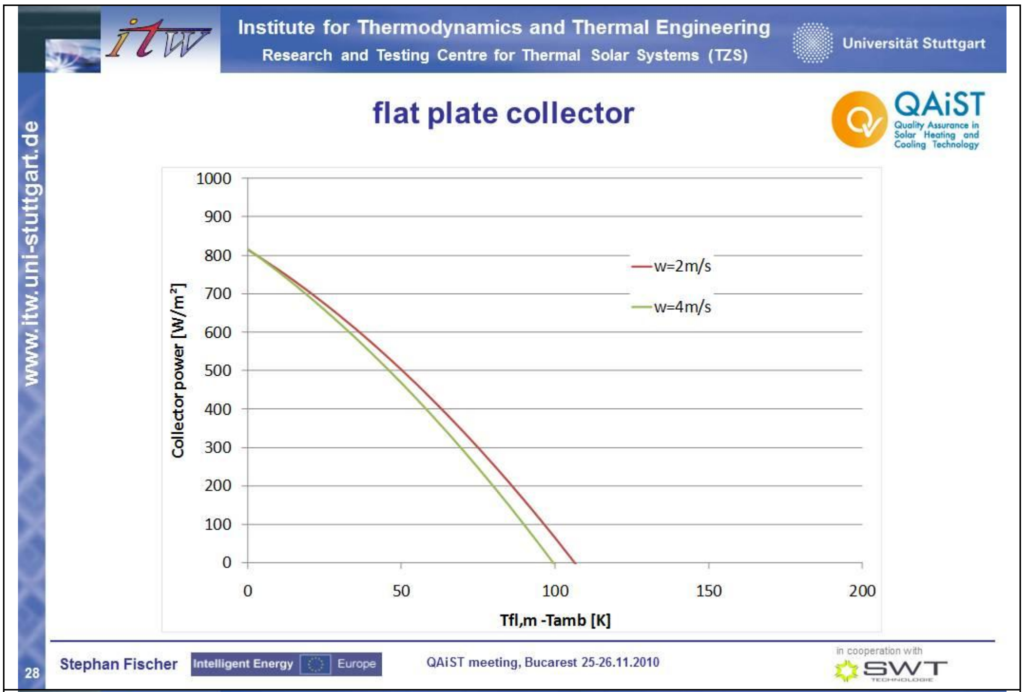
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flat plate collector
Collector power [W/m²]
1000
900
800
700
600
500
400
300
200
100
0
0
50
100
150
200
Tfl,m -Tamb [K]
w=2m/s
w=4m/s
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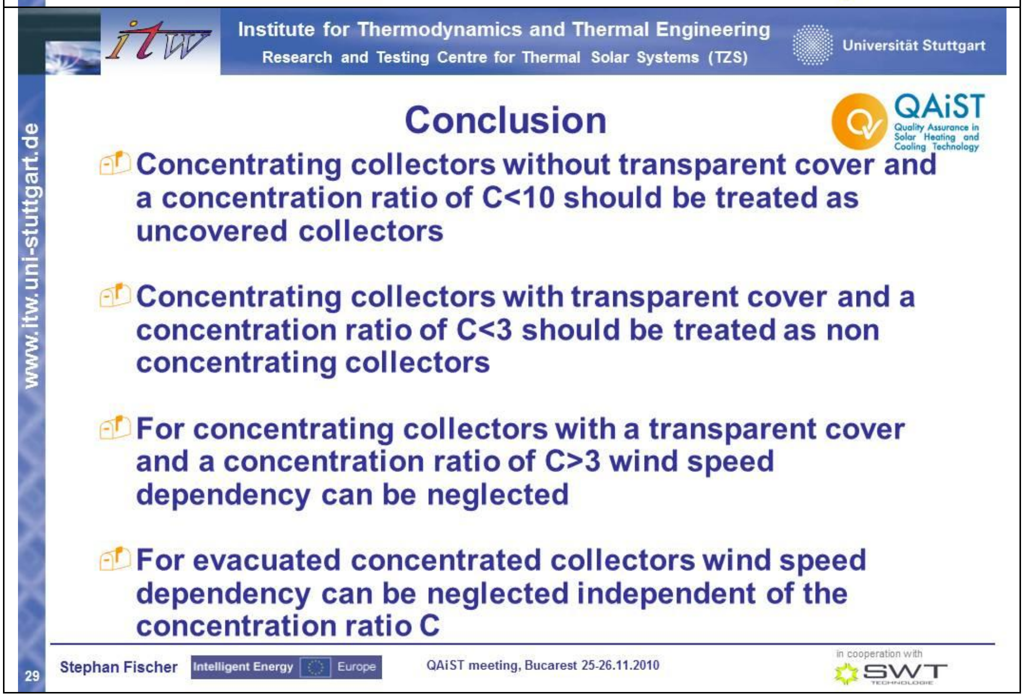
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Conclusion
Concentrating collectors without transparent cover and a concentration ratio of C<10 should be treated as uncovered collectors
Concentrating collectors with transparent cover and a concentration ratio of C<3 should be treated as non concentrating collectors
For concentrating collectors with a transparent cover and a concentration ratio of C>3 wind speed dependency can be neglected
For evacuated concentrated collectors wind speed dependency can be neglected independent of the concentration ratio C
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Annex 2: Working paper on performance measurement at elevated temperatures

Idea

ISFH

Several studies have been done by SP (NEGST) and ISE concerning performance tests at higher temperatures (near 100°C). ISFH will do performance tests up to temperatures significantly above 100°C (aim is about 140°C). Tests will be carried out at collector types designed for higher working temperatures (ETC, double-glazed FPC) and additional on a standard FPC

- discrepancy in extrapolation esp. for operation at higher temperatures
- development of a_2 at ETC with dewar tubes (in common performance testing procedure a_2 at ETC with dewar tubes is nearly negligible)

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Test facilities

ISFH

Performance tests of collectors according to EN 12975 at fluid inlet temperatures up to 175°C

- fluid, pressure — water (12 bar), water/glycol (6 bar)
- temperature — 15…175°C water, 15…140°C water/glycol, control accuracy ± 0.05 K
- mass flow — 50…1000 kg/h, control accuracy ± 1%
- test area — 1 x 4 m² and 2 x 10 m²
- mobile facility — indoor measurements (sun simulator)

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Test facilities

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Hurdles

- There is no experience concerning the influence of the fluid temperature on the accuracy of devices for determining the mass flow
- The standards (EN 12975-2, ISO 9806-1, ISO 9459-5…) contain (different) tables or regression formulas for the thermal capacity and density of water related to a pressure of 1 bar and temperatures from 0°C to 100°C. There is a need to extend the data to higher temperatures and even (corresponding) higher pressures

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State of works

- A procedure for high temperature calibration of devices for determining the mass flow has been developed
  - the calibration of different mass flow metres (coriolis) and volume flow meters (MID) is in process
  - the reproducibility is good
  - due to the power of thermostats the highest temperature for calibration has reached 136°C by now

the influence of temperature seems to be negligible for the actual tested devices

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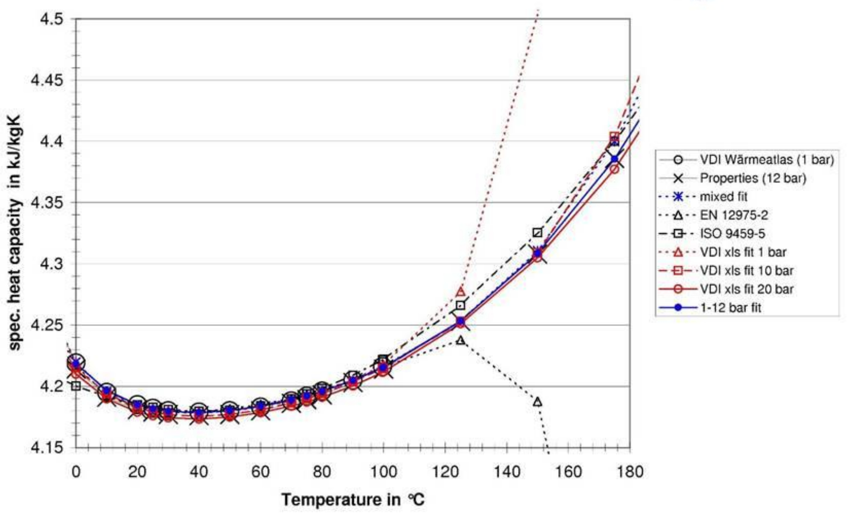
State of works



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State of works

Different Fits based on the data tables from VDI Wärmeatlas were made and compared

- -A mixed fit uses data given for 1bar from 0°C to 99°C and those for 5 bar from 100°C to 150°C (sigma plot for fitting)
- -The other fits are based on the tables for the different pressures (as stated in the graph, excel for fitting)
- -A fit made with the aim to have for 1 bar up to 12 bar low deviations (related to VDI Wärmeatlas (1bar) and Properties of Water and Steam (12 bar))

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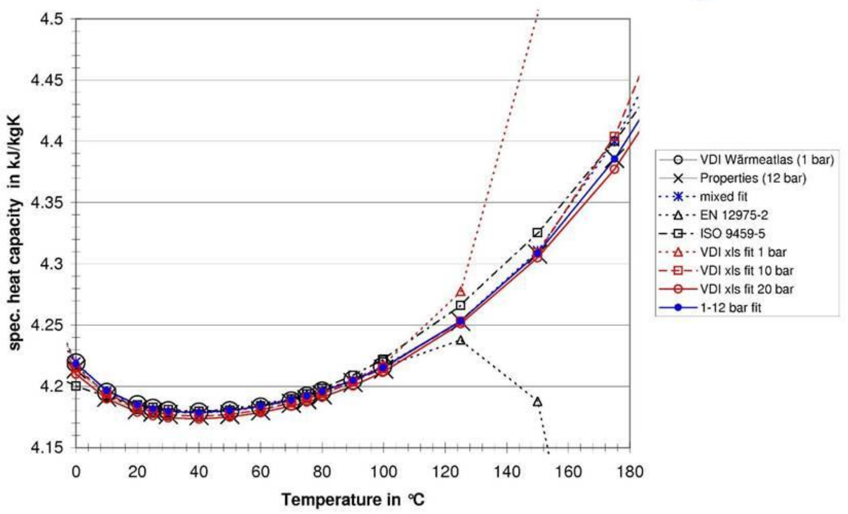
State of works



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State of works

$c_p(\vartheta) = 4.2184$
$- 2.8218exp{-03} \times \vartheta$
$+ 7.3478exp{-05} \times \vartheta^2$
$- 9.4712exp{-07} \times \vartheta^3$
$+ 7.2869exp{-09} \times \vartheta^4$
$- 2.8098exp{-11} \times \vartheta^5$
$+ 4.4008exp{-14} \times \vartheta^6$

mean deviation related to 12 bar 0°C to 185°C 0.059%, related to 1 bar 0°C to 99°C 0.013%

Temperature	Heat capacity	Deviation	
°C	KJ/kgK	% rel to VDI 1 bar	% rel to IAPWS 12 bar
0	4.218	0.0142	-0.1044
10	4.197	-0.0394	-0.1349
20	4.185	0.0034	-0.0923
30	4.180	0.0106	-0.0612
40	4.178	0.0135	-0.0583
50	4.180	-0.0016	-0.0734
60	4.184	-0.0162	-0.0880
70	4.189	-0.0231	-0.0708
80	4.196	0.0018	-0.0698
90	4.205	0.0065	-0.0410
100	4.216		-0.0379
125	4.253		-0.0082
150	4.308		-0.0101
175	4.385		0.0118
185	4.425		-0.0064

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Next steps

Comparing determination of collector performance according to minimum requirement of EN 12975-2 (6.1.4.4 highest mean collector fluid temperature at least 80°C) with efficiency data resulting in measurement up to at least 140°C at three different series collectors

- Standard single glazed flat plate collector
- Dubble glazed flat plate collector
- Evacuated tubular collector with dewar tubes (collector from Round Robin test)

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QAiST
Quality Assurance in Solar Heating and Cooling Technology
Next steps
ISFH
Check different fits for density
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Leibniz
Universität
Hannover