SOLAR HEATING & COOLING PROGRAMME
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IEA-SHC TASK 43: SOLAR RATING AND CERTIFICATION PROCEDURES

White Paper on Concentrating Collectors

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1 SUMMARY

This report summarizes the work carried out in the field of concentrating and tracking solar thermal collectors. The goal of this work was the introduction and validation of a test method capable of treating concentrating as well as concentrating/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 addressing testing of concentrating and tracking collectors.

Section 3 (Status of the standardization work related to concentrating collectors) discusses the implementation of updated standard EN ISO 9806.

Section 4 addresses Definitions and Requirements

Section 5 (Review of Performance Models, Test Procedures, and Test Conditions) presents a comprehensive review and analysis of existing standards and test procedures. In addition, a summary of equations used to calculate the end losses of single collectors as well as the end gains achieved when several collectors are installed in series is presented.

Section 6 (Concentrating Collector Tests) describes the quasi-dynamic collector model and points out the necessity to distinguish between diffuse and beam irradiance when testing concentrating collectors, and shows how the quasi-dynamic method should be used for testing concentrating solar collectors. This section applies the procedure to two different CPC collectors and two different parabolic trough collectors, showing that these measurements have the same accuracy as the results for conventional flat plate and evacuated tubular collectors.

Section 7 (Collector Component Characterization, Durability and Reliability) discusses durability and reliability test methods for concentrating collectors and individual components of collectors.

Section 8 (Text Proposals for Standard Revision) lists the main text which needs to be included in the next revision of the EN 12975. In addition to addressing the necessary terms and definitions related to concentrating and tracking collectors, changes to the existing test procedure are described. Equations describing the thermal properties of water up to a temperature of 185 °C and a pressure of 12 bar are given.

Section 9 (Proposal for future work) Discusses the five most pressing issues for further work needed to bring forward the technology of mid temperature collectors including tracking and concentrating collectors from the point of view of the consortium.

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

Concentrating as well as concentrating/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 modifiers 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 above factors.

2.1 Definition of the conversion factor

The conversion factor η0 for flat plate and evacuated tubular collectors is defined by the product of the collector efficiency factor F' and the transmission-absorbance-product (τα) (equation 1).

$$\eta_0 = F'(\tau\alpha) \qquad (1)$$

For concentrating and concentrating/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).

$$\eta_0 = F'(\tau\alpha)\rho\gamma \qquad (2)$$

2.2 Incidence angle modifier for concentrating and tracking collectors

2.2.1 Stationary compound parabolic concentrating collectors

CPC collectors have, similar to evacuated tubular collectors, a biaxial behavior 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 changes 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 **Error! Reference source not found.**.

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

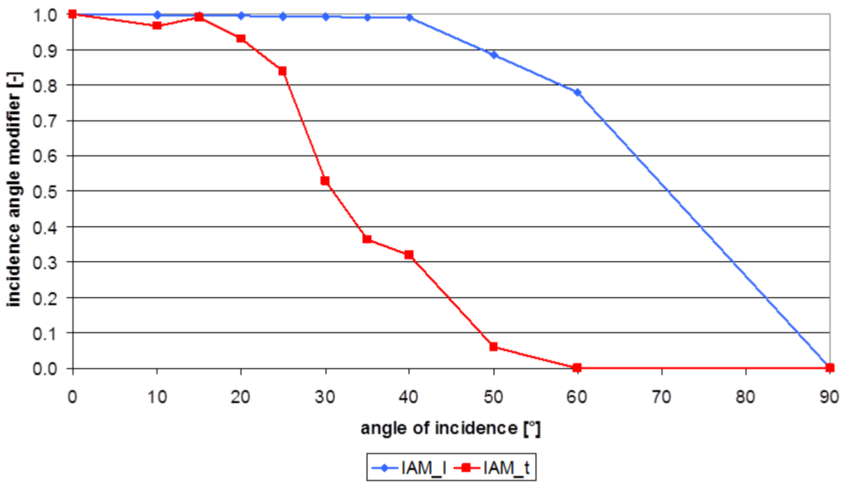

Figure 1: Incidence angle modifiers for a CPC collector

2.2.2 Concentrating and tracking collectors

Three different incidence angle modifiers apply to concentrating and tracking collectors:

1. A bi-axial incidence angle modifier similar to evacuated tubular or CPC collectors applies for linear Fresnel collectors.
2. For the class of parabolic trough collectors the bi-axial behavior reduces due to a single axis tracking behavior. In this case the longitudinal incidence angle is the incidence angle of the collector since the transverse 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.

2.2.3 Impact of diffuse irradiance on the performance of concentrating collectors

The thermal performance of concentrating collectors is significantly dependent on the concentration ratio C, as well as other factors. The concentration ratio for collectors having tubular absorbers is calculated by the ratio between aperture area and "unrolled" absorber area. This can also be described by assuming that the diffuse irradiance available for the collector is reduced by the quotient 1/C. Using this assumption the irradiance Gnet 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 Gnet 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 Gnet on the concentration ratio C significant attention must be directed at the determination of thermal performance of concentrating collectors as 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 = Gdfu/G. High concentration ratios and high diffuse fractions demonstrate a low value of useful irradiance fraction.

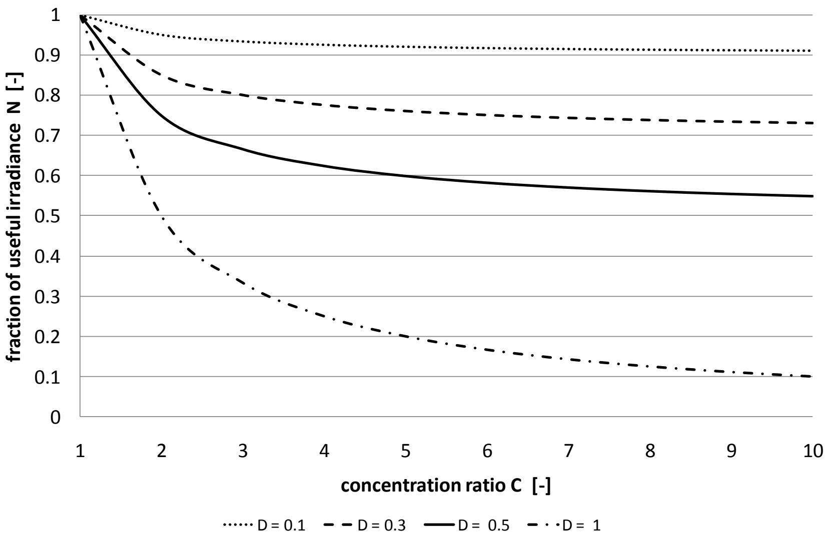

Figure 2: Fraction of useful irradiance N as a function of the concentration ratio C and the diffuse fraction D

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 STATUS OF STANDARDIZATION WORK RELATED TO CONCENTRATING COLLECTORS

In large part due to the work carried out in IEA Task 43, concentrating and concentrating/tracking collectors are now accommodated within the scope of the new draft of ISO/DIS 9806. The draft will be out for final vote in the middle of the year, and is expected to be published as EN ISO 9806 by the end of the year 2013, or early in 2014.

The EN ISO 9806 will become a joint European/ISO Standard, and will replace the following standards:

- EN 12975-2
- ISO 9806-1
- ISO 9806-2
- ISO 9806-3

4 DEFINITIONS AND REQUIREMENTS

A new set of definitions related to concentrating collector technologies has been developed. This set of definitions was initiated within the EU QAIST1 project with the objective of being part of the new EN12975 standard revision which will include performance and durability tests for concentrating/tracking collectors.

As a base for this set of definitions the following standards and technical papers have been taken into account:

- ISO 9488:1999 Solar Energy Vocabulary
- ISO 9806-1:1994 and ISO 9806-2:1994

[1] QAIST: Quality Assurance in solar thermal heating and cooling technology. Intelligent Energy Europe. IEE/08/593/SI2.529236"

- ANSI+ASHRAE 93-2003
- CAN-CSA-F378-87(R2004)-Collectors-2412326
- ASTM E905 - 87 (2007)
- SRCC OG 600
- Paper_Standards_Oxaca-draft227 (Lüpfert et al.)
- Biggs,1979 / Duffie,1980 / Falcone and Kistler,1986 / Montes-Pita,2008
- Stine,2001 / Forristal,2003 / SAM,2009
- Eickhoff,2002 / Fisher,2004 / Perers,1997

The initial set of definitions was revised within the IEA-SHC Task 43 - Subtask A with participants from around the globe in several meetings.

The final goal is to include the revised set of definitions into the standard ISO 9488 Solar Energy Vocabulary but due to the following reasons it has not been possible:

- The urgency of CEN Technical committee 312 (CEN TC 312) to submit the EN12975:2011 first draft to CEN (European Committee for Standardization) in April 2011.
- The fact that the ISO 9488 revision process under ISO technical committee 180 (ISO TC 180) lead, already open at that time, but showing not much activity. So, CEN TC312 decided to include the set of definitions in Part 2 of the EN12975:2011 first draft as a temporary measure, and sent to the ISO TC180 the set of definitions as an input for the ISO 9488 revision process.
- Parallel to the ISO 9488 revision process the ISO TC180 decided to start the revision process of the ISO 9806 Test methods for solar collectors adopting the advances of the EN12975:2011 revision. ISO TC180 and CEN TC 312 agreed to develop a common and global standard for solar thermal collectors.

The set of definitions includes the following concepts, which at the moment are not present in the ISO 9488 standard for Solar Energy Vocabulary:

Acceptance angle, Cleanliness factor, Collector optical axis, Collector rotation axis or tracking axis, Collector useful power, Combined assembly, Concentrator, Concentrator axis, Cosine loss, End effects, Fail-safe, Incident angle modifier, Intercept factor, Longitudinal angle of incidence, Longitudinal plane, Maximum operating temperature, Minimum acceptance angle, Module, Nominal collector power, Near-normal incidence, Non-concentrating collector, No-flow condition, Outgassing, Optical efficiency or zero loss efficiency, Passive, Peak efficiency, Peak optical efficiency, Peak power, Quasi-dynamic test, Rated performance, Receiver aperture, Receiver efficiency, Reconcentrator, Reflector or reflective surface, Rim angle, Shadowing, Site assembled collector, Specular reflectance, Spillage, Sunshape, Thermal performance, Tracking angle, Transversal angle of incidence, Transversal plane and Trigger or safety activation temperature.

One limitation of the elaborated definitions is that they are valid mainly for linear focus concentration systems, but sometimes not applicable for point focus or central receiver systems. Related definitions about tracking systems can be also found in the IEC specifications for solar trackers used in photovoltaic systems.

5 REVIEW OF PERFORMANCE MODELS, TEST PROCEDURES, AND TEST CONDITIONS

A comprehensive review analysis of the existing standards has been performed. The review includes the following standards for performance test procedures of solar thermal collectors: ASHRAE 96, ISO9806-3, EN 12975-2:06 Chapter 6.1 (steady state), EN 12975-2:06 Chapter 6.3 (quasi-dynamic), CAN-CSA-F378-87(R2004)-Collectors-2412326, ASTM E905-87 (2007), SRCC Standard 600 Rev. 9/09.

The review has considered the following aspects from the previous standards:

- Purpose and scope:
  - Test method
  - Collector type
  - Heat transfer fluid
  - Exceptions
- Test conditions:
  - Test procedure
    - Number of data points
    - Measurement interval
    - Length of the pre data and data periods
    - Minimum number of required test days
    - Reference irradiance
  - Set points for controlled variables
    - Inlet temperature distribution
    - Mass flow rate
  - Allowed range of uncontrolled variables (absolute limits)
    - Total solar irradiance and diffuse irradiance on collector plane
    - Incidence angle (angle between beam radiation and collector normal)
    - Relative thermal radiation
    - Wind speed
    - Ambient temperature and ambient temperature range between all data points
  - Allowed variation of controlled and uncontrolled variables (steady state or quasi-dynamic conditions)

- Inlet temperature
- Inlet flow rate
- Temperature difference between inlet and outlet
- mC_p value
- Total solar irradiance and long wave irradiance on collector plane
- Direct solar irradiance
- Ambient temperature
- Wind speed
- Heat transfer fluid density and specific heat

- Magnitudes and measurement devices
  - Direct solar irradiance
  - Total solar irradiance on collector plane
  - Solar simulator
  - Tracking system and associated controls

- Measurement accuracy
  - Total solar irradiance on collector plane
  - Direct solar irradiance
  - Angular measurement
  - mC_p - Product determination
  - Temperature difference
  - Tracking system and associated controls

- Tests method procedures:
  - Response time
  - Incident angle modifier
  - Rate of Heat Gain at Near-Normal incidence
  - Near normal incidence for tracking accuracy requirements (optional). Effect of tracking errors to the collector thermal performance
  - Heat Gain at near normal incidence
  - Angular range of near-normal incidence

As a result of the review analysis several performance test conditions have been revised for the quasi-dynamic test method which has been selected as the most flexible and suitable testing procedure for concentrating/tracking collectors.

5.1 Collector performance model and Parameters

The collector performance model according to Equation 1 should be used to characterise the collector output of concentrating collectors.

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

With:

a_1	[W/(m²K)]	Heat loss coefficient
a_2	[W/(m²K²)]	Temperature dependent heat loss coefficient
A	[m²]	Aperture area
c_{eff}	[J/(m²K)]	Effective heat capacity of the collector
G_{dfu}	[W/m²]	Diffuse irradiance
G_{beam}	[W/m²]	Beam 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

5.2 Testing conditions

5.2.1 Impact of wind speed on performance measurement

To assess the impact of the wind speed on the performance measurement an extensive theoretical evaluation was carried out, see Annex A, resulting in the following findings:

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.*

5.3 Treatment of end losses for linear concentrating collectors

In addition to the optical losses due to optical dependency of glass, absorber mirrors, etc. from the angle of incidence (see equation 2 according to Beckmann), linear concentrating collectors underlie additional losses caused by the geometry, the so-called end losses.

$$\cos\theta = \sin\phi(\sin\delta\cos\beta + \cos\delta\cos\gamma\cos\omega\sin\beta) + \cos\phi(\cos\delta\cos\omega\cos\beta - \sin\delta\cos\gamma\sin\beta) + \cos\delta\sin\gamma\sin\omega\sin\beta \quad (2)$$

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 1**:**). Thus the focus is beyond the length of the absorber tube (Trieb, et al., 2004), (Muthusivagami, 2011).

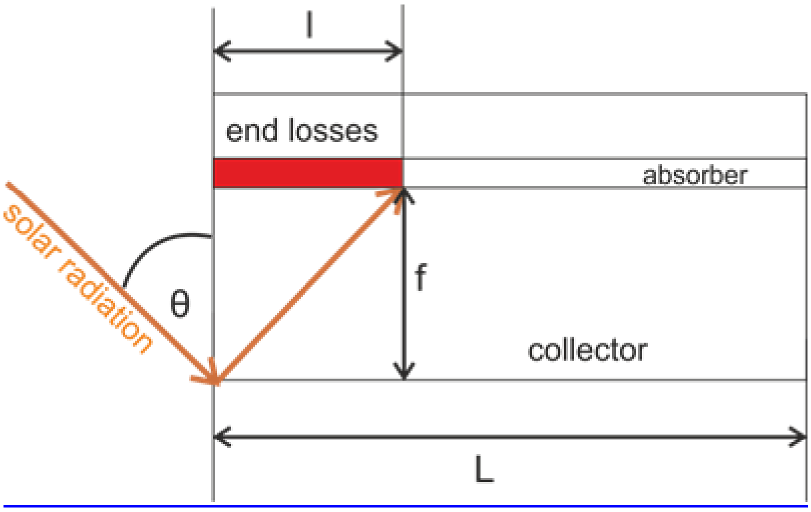

Figure 1: Geometric sketch of a parabolic trough

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)

$$l = f \cdot \tan\theta \quad (3)$$

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

In several references the end loss is defined according to equation (4), see (Muthusivagami, 2011) and (Patnode, 2006).

$$End\ loss = 1 - \frac{l}{L} = 1 - f\,\frac{\tan\theta}{L} \quad (4)$$

With
L = length of the linear concentrating collector

This definition is misleading, because end losses are actually the ratio of l to L. In this publication the definition in equation (5) is introduced.

$$IAM_{endloss} = 1 - \frac{l}{L} = 1 - f\,\frac{\tan\theta}{L} \qquad (5)$$

Another definition of the end losses are given by (Beckmann, et al., 2006), see equation (6).

$$IAM_{endloss} = 1 - \frac{f}{l} \cdot \left(1 + \frac{a^2}{48 f^2}\right) \cdot \tan\theta \qquad (6)$$

With
a = aperture width of the trough collector

The term $\left(1 + \frac{a^2}{48 f^2}\right)$ of equation (6) 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 (5) 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:

$$IAM_{endloss} = 1 - 5 \cdot \frac{\tan 45}{50} = 0{,}92 \qquad (7)$$

Resulting from formula (5): The smaller the f/L ratio, the smaller are the end losses. This context is shown in Figure 2 for different f/L ratios.

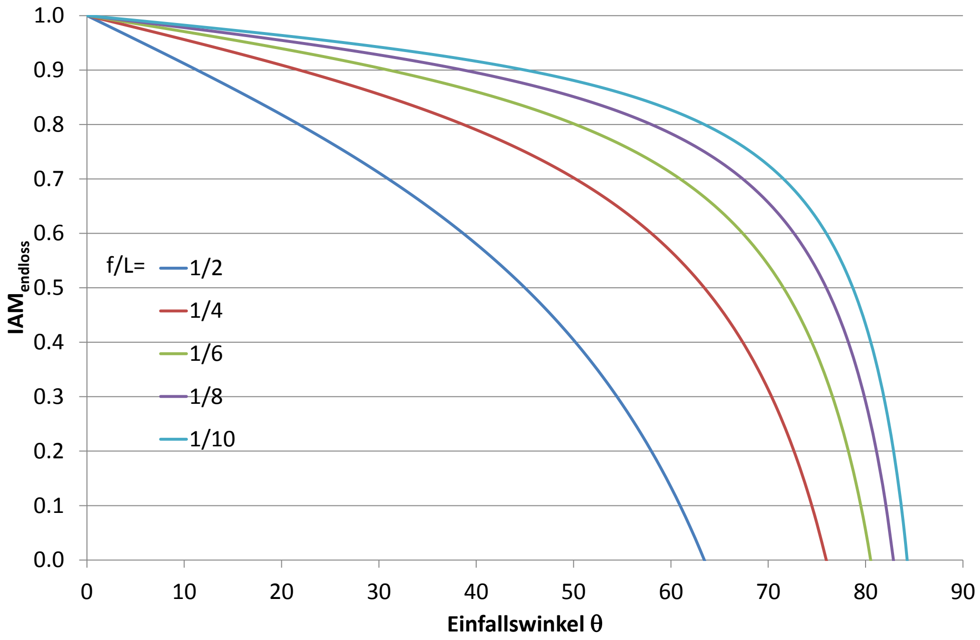

Figure 2: $IAM_{endloss}$ for different f/L ratios

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 3). The length of the illuminated absorber tube of the next collector can be calculated with formula (8) (Larcher, 2012).

$$l_{win} = f \cdot \tan\theta - d_D \tag{8}$$

With

d_D = distance between the linear concentrating collectors

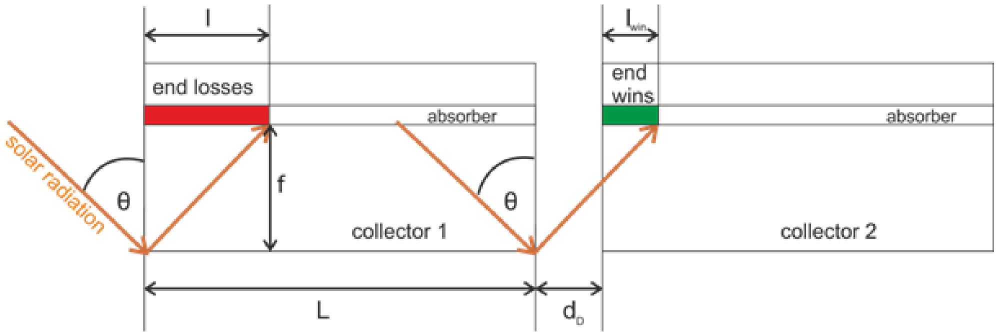

Figure 3: Geometric sketch of two parabolic trough collectors

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%.

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

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6 CONCENTRATING COLLECTOR TESTS

6.1 Tests of compound parabolic concentrating 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.

6.1.1 CPC Collector 1

CPC collectors (see figure 1) use a Compound Parabolic Concentrator as a 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 constitute a logical link between flat plate collectors and evacuated tube collectors.

Figure 1: CPC collector 1

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. Currently, thermal performance is determined using test methods under both the steady state as well as quasi-dynamic conditions.

This section compares the results obtained using 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 more detailed test method using **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 possible to model the influence of the beam irradiance under different incident angles. Also, the effect of the diffuse fraction of total insolation on thermal performance can be measured. In addition, the utilization of the effective heat capacity c_{eff} in the thermal performance model of the collector (see equation 1) allows for a description of the dynamic behaviour of the collector under changing radiation levels. By means of the quasi-dynamic test method the thermal performance of stationary non-concentrating collectors and tracking concentrating collectors can be determined. 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** does not differentiate between beam and diffuse irradiance in order to calculate 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(θ), 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. The impact of this fact on the test results of CPC collectors is described as follows.

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.

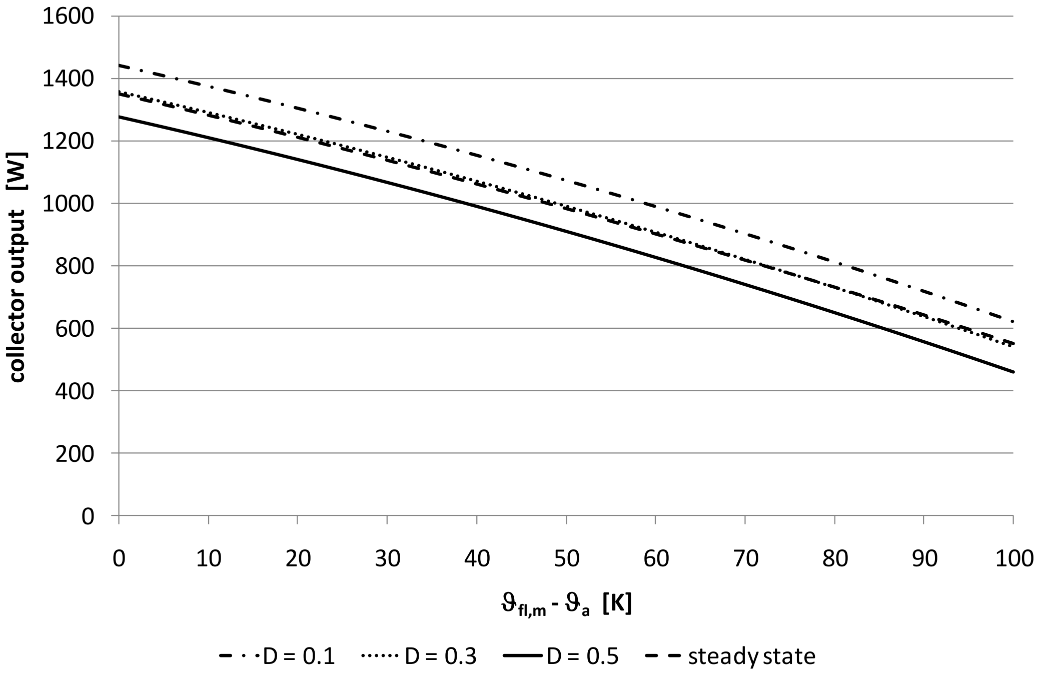

Figure 2: Power curves (G = 1000 W/m²) for different diffuse fractions and under steady state conditions

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 result is attributed to the fact that the mean diffuse fraction during the test under steady state conditions has been D = 0.3.

From this investigation 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

In contrast to the test method under steady state conditions, the quasi-dynamic method is very well suited to determine the thermal performance of CPC collectors having a concentration ratio larger than 1. The differentiation between diffuse and beam irradiance permits a reliable modelling of 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 sizing of solar thermal systems using CPC collectors.

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

As markets for solar thermal process heat and solar cooling are growing, increasing numbers of concentrating collectors are being introduced in Europe. Against this background it is appropriate to codify the test method under quasi-dynamic conditions as the sole allowable test method to be used for concentrating collectors with 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.

6.1.2 CPC Collector 2

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 also analyzed. The peak efficiency for this collector was achieved with an offset from the normal of 10-12 degrees in the transverse direction, which raised some questions around the testing procedure and the way results are reported. Long term measurements were performed on the tested collector using a constant inlet temperature in order to validate the collector model.

The tested collector is shown in Figure 4 and Figure 5. It is of light weight construction, without insulation, and uses 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 mounted on a wall or a tracker.

Figure 4 The CPC collector's transverse IAM measured with collector in vertical orientation (N-S**)**

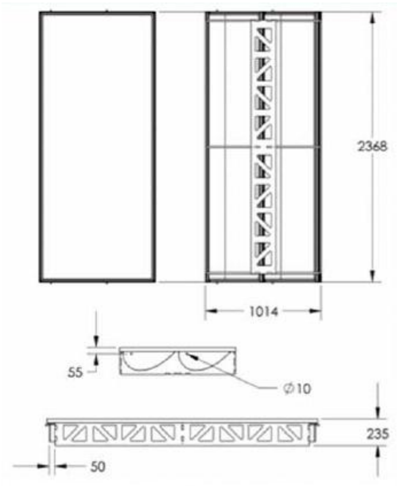

Figure 5 Drawing of the CPC collector

In order to reduce overheating problems, the design of this particular 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 positions:

1. Collector oriented horizontally, with the absorber strips in the east-west direction
2. Collector oriented vertically, with the absorber strips in the north-south direction, see Figure 4.

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 close to the autumnal equinox in order to have a more or less negligible influence of the transverse IAM on the results when determining the longitudinal IAM.

<u>Testing results</u>

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 6.

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[2] [-]				$K_{\theta d}$ = 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

[2] $F'(\tau\alpha)_{en}$ = 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

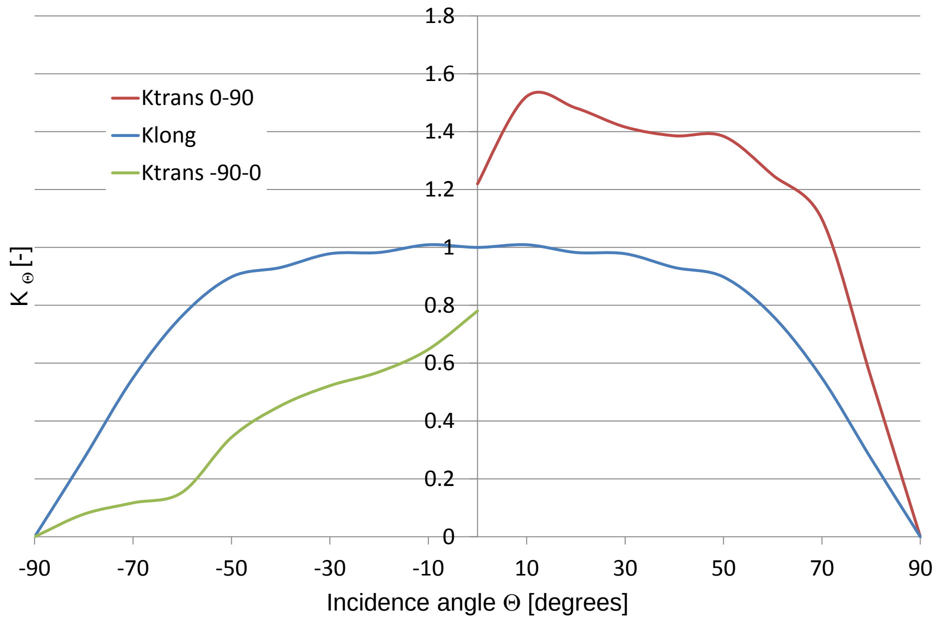

Figure 6. Transverse and longitudinal IAM referring to the efficiency at normal incidence

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 7.

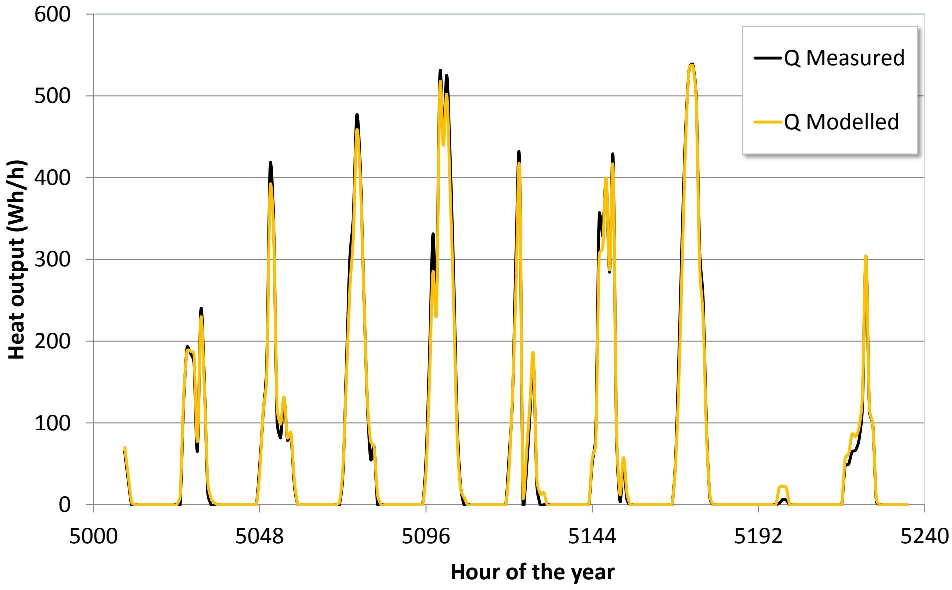

Figure 7: Hourly values of measured and modelled performance of the CPC collector

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 8 showing relative deviations of 0,5; 2,7 and 3,5 % for July, August and September respectively. However, on an hourly timescale the relative deviations can be significant.

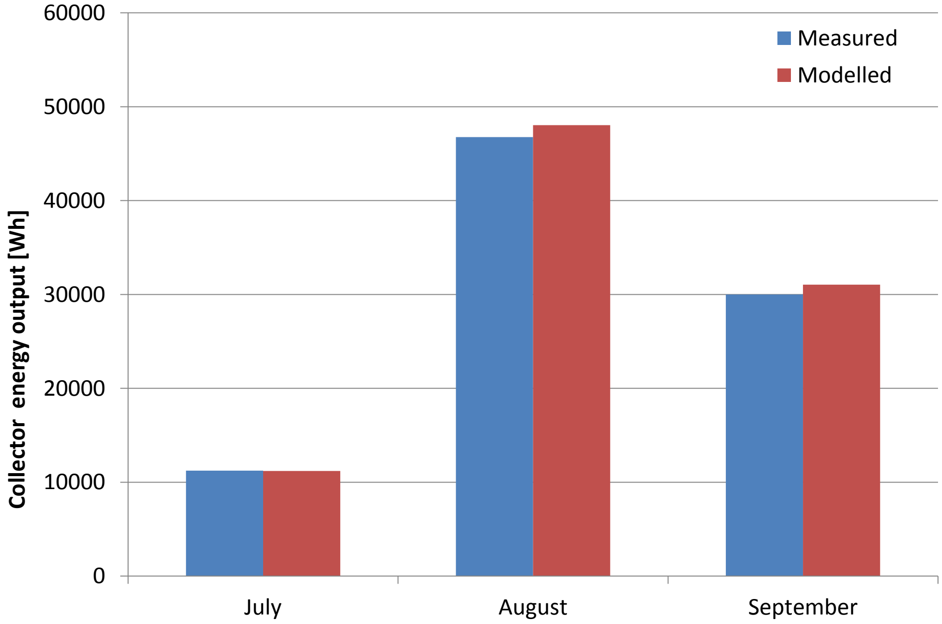

Figure 8: Measured and modelled monthly energy yields for the tested CPC collector. All monthly results show agreement better than 5%.

6.2 Tests of midsize parabolic trough collectors

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 0.

6.2.1 Test of parabolic trough collector 1

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 involved in the design of a solar thermal system, including designers, investors, operators and last but not least collector manufacturers. 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 decades [1], [2]. These Standards are well accepted for the test of flat plate collectors and evacuated tubular collectors. However, in regards to collectors with a significant concentration ratio, the use of the hemispherical solar irradiance as reference irradiance does not meet the requirement for performance characterization. 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 differing nomenclatures and methodologies applied to a variety of collector models. 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 product identity was eliminated by the introduction of 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. An incident angle modifier is applied to both values, $K_{\theta b}(\theta)$ is a function of the angle of incidence of the direct irradiance and the constant $K_{\theta d}$ is used for 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 were used covering clear sky scattered clouds conditions. 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 (below) show the direct irradiance G_b, diffuse irradiance G_d and the specific collector output P_{col} per aperture area during two test sequences.

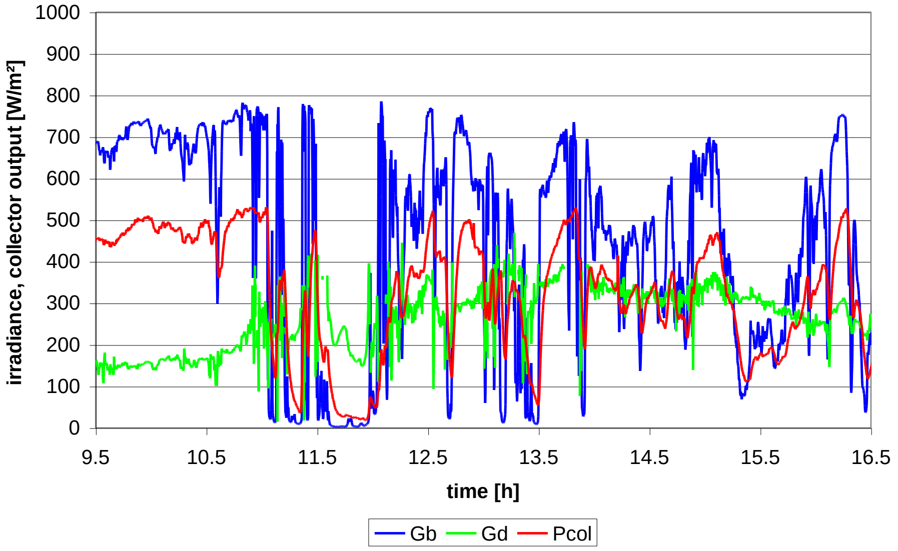

Figure 1: Test sequence 2, unstable irradiance

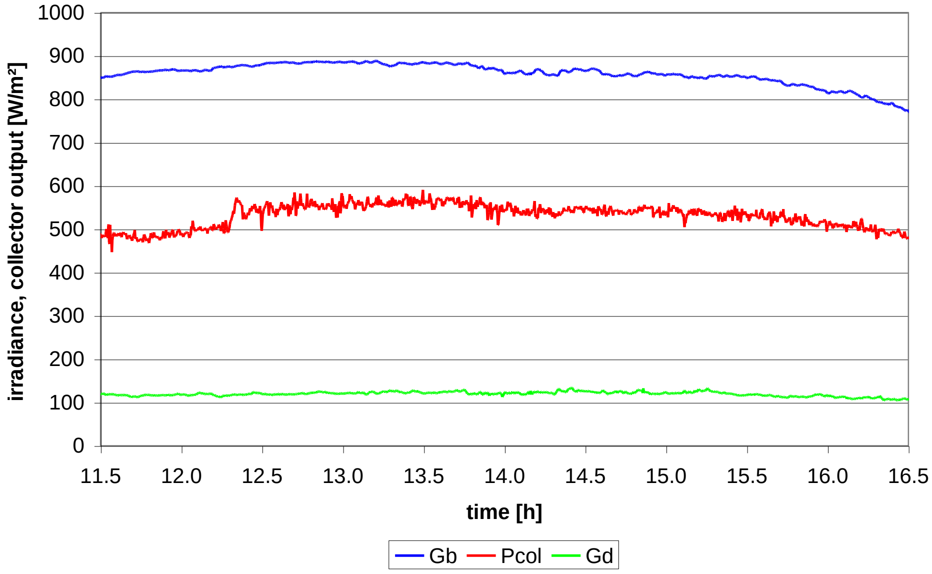

Figure 2: Test sequence 5, on a clear day

Parameter identification and results

For the evaluation of the measured data Multiple Linear Regression (MLR) as the parameter identification tool can be used [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 tools 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

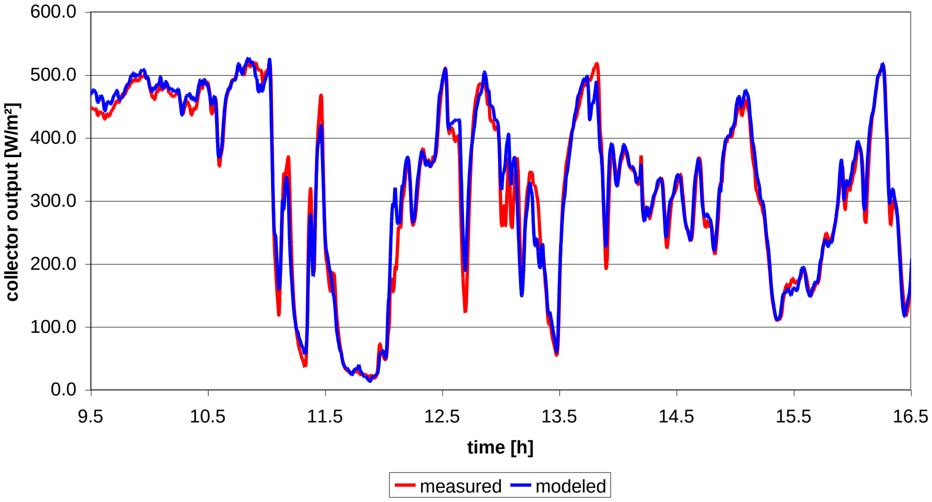

Figure 3: Measured and modeled collector output of test sequence 2

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. During the testing period of 5 days a variety of sky conditions occurred, allowing the accumulation of sufficient data to extract the relevant collector performance parameter set.

Thus, using European Standard EN 12975, performance testing for flat plate, evacuated tubular, and 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

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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.

6.2.2 Test of parabolic trough collector 2

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The test described in section 5.2.1 was carried out with two-axis tracking. As a consequence, the incident 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.

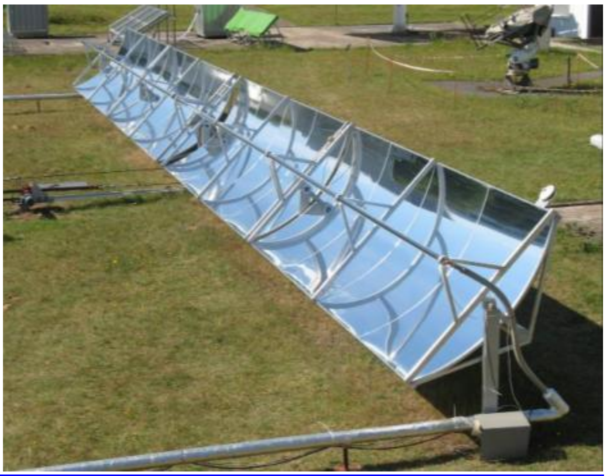

Figure. 1: Parabolic trough collector under test

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:

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

and modelled afterwards according to:

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

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. 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 from 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 a collector 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 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:

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

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.

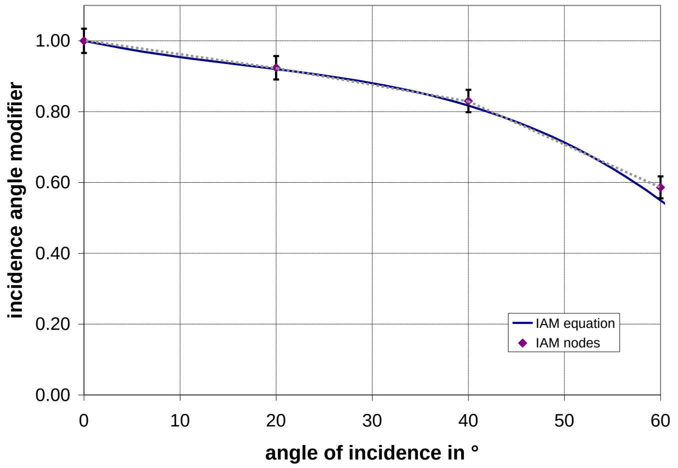

Figure 2: Collector IAM as a function of angle of incidence comparing the IAM equation and node approach

For future work the IAM model using nodes is 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.

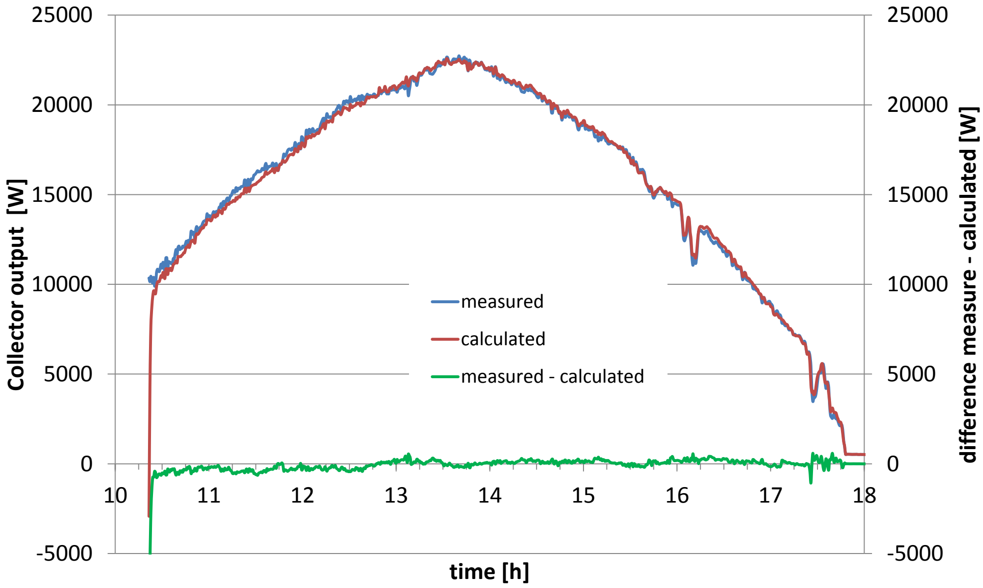

Figure 3: Measured and calculated collector output for test day #5 according to table 1

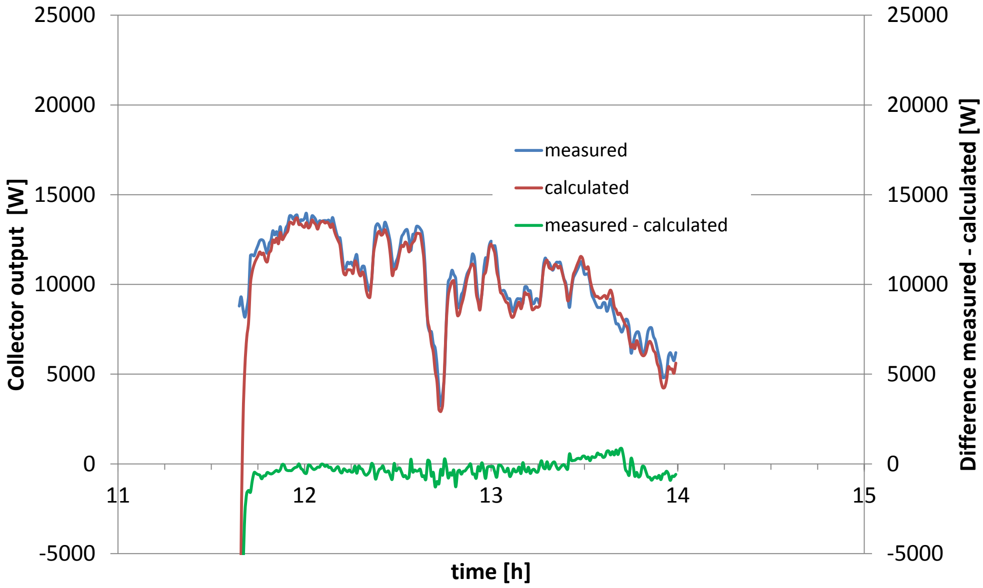

Figure 4: Measured and calculated collector output for test day #6 according to table 1

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)
$K_{\vartheta b}(\vartheta)$	-	incidence angle modifier for beam irradiance
$K_{\vartheta d}$	-	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

7 COLLECTOR AND COMPONENT CHARACTERIZATION, DURABILITY AND RELIABILITY

7.1 Durability and reliability test for concentrating/tracking collectors

The present standards ISO 9806 and EN 12975-2 describe the thermal performance and durability tests for solar collectors, however the durability tests are not applicable to concentrating/tracking collectors.

The EN 12975-2:2011 revision includes additional paragraphs describing the reliability testing of concentrating and/or tracking collectors. The advances of the EN 12975 revision will also be adopted in the present ISO 9806 revision process. These advances are described in the following sections, 0 and 0.

7.1.1 General requirements

- Concentrating collectors shall demonstrate suitable performance and ability to protect themselves from common failures in standard operation during their lifetime.
- The collector shall be assembled according to manufacturer's specifications. If the collector has active mechanisms those mechanisms shall be operational during testing and shall be supplied by manufacturer. Concentrating collector designs which include a factory sealed container charged with a fluid used in the collection of heat shall be tested without the removal of this element.

- The protection systems can be active or passive. The manufacturer shall define the equipment protection features and if the equipment require an external energy supply to operate or not.
- The collector can present a combination of active and passive controls, so the test sequence shall be selected to verify suitable operation of controls during normal operating conditions.

7.1.2 Reliability tests

Exposure test

The test shall be performed according to the procedure described in the corresponding section of the EN 12975-2:2011 (similar to the EN 12975-2:2006 procedure), but taking into account the following indications:

- Concentrating collectors shall be tested in outdoor exposure conditions, and all their components and subsystems shall be validated to be functional during the exposure period. If the collector includes active systems they shall be active and operational during the exposure test.
- Collectors shall be mounted outdoors but shall not be filled with heat transfer fluid, unless controls are used to manage both a no-flow and high temperature condition according to the manufacturer's instructions. In that case, collectors shall be filled with the heat transfer fluid and such controls shall be verified.
- Collector designs which include a factory sealed container charged with a fluid used in the collection of heat shall be tested without heat transfer fluid flowing through them unless controls are used for over temperature protection.
- At least once a week, collectors shall be subjected to visual inspection and any change in the physical appearance shall be registered and reported with the test results.

Active and passive control test

The manufacturer must identify all active and passive protection controls which are present in the collector. The manufacturer shall submit their control set points and parameters in order to verify their suitable operation during normal working conditions.

A test cycle during the exposure period will be established for testing the active and/or passive controls which are necessary to keep the collector in working conditions. Their operation shall be validated to be functional, in such a way that any failure can be detected. The test cycle shall include as events the loss of electrical supply and the blockage of tracking mechanism (if present). The verified control functions shall be described and reported with the test results.

High temperature resistance test

The test shall be performed according to the procedure described in the corresponding section of the EN 12975-2:2011 (similar to the EN 12975-2:2006 procedure), but taking into account the following indications:

- High temperature resistance test shall be carried out during the exposure test.
- If controls are present to manage both a no-flow and high temperature condition, the collector must be filled with heat transfer fluid and it should not be able to reach stagnation conditions. Such controls shall be validated to be functional and the collector shall reach the maximum operating temperature defined by the manufacturer.
- The verified control functions shall be described and reported with the test results.

Internal thermal shock test

The test shall be performed according to the procedure described in the corresponding section of the EN 12975-2:2011 (similar to the EN 12975-2:2006 procedure), but taking into account the following indications:

- It is not applicable to those parts of the collector which are factory sealed.
- It is not applicable to those collectors in which heat transfer fluid is continuously flowing for protection purposes. In that case control(s) used to manage a no-flow condition shall be validated to be functional in such a way that any failure can be detected.
- The verified control functions shall be described and reported with the test results.

Mechanical load test

The test shall be performed according to the procedure described in the corresponding section of the EN 12975-2:2011 (almost like the EN 12975-2:2006 procedure), but taking into account the following indications:

- As concentrating collectors have different geometries, specific and suitable procedures must be designed to test resistance against mechanical load. The procedure carried out shall be clearly described with the test results.
- When according to the manufacturer’s instructions, controls are present to protect the collectors against wind or snow load, the control functions shall be validated to be functional, if it is possible, and they shall demonstrate resistance to failures associated with collector normal operation.
- The verified control functions shall be described and reported with the test results.

The following tests will be performed as described in the corresponding chapters of the EN12975-2:2011 standard (test procedures nearly identical to the EN12975-2:2006 for non concentrating collectors: flat plate or evacuated tube):

Internal pressure test for absorbers

Rain penetration test

External thermal shock test

Impact resistance test

Final inspection and test report

7.2 Component performance and durability test methods

At this time, most of the components which are part of a concentrating/tracking collector have not been addressed for standardized testing procedures. Mainly, the existing performance and durability test procedures for concentrating collector components like reflectors or receivers come from research and development activities for Concentrating Solar Power (CSP) applications.

In the near future, the recently created IEC Technical Committee 117 for solar thermal electric plants (AENOR secretariat) will deal with standardized performance and durability test procedures at different levels: from collector components to the complete CSP plant. This standardization process is lead by the CSP market due to its rapid growth and the increasing requirements on quality, durability and service life time for the solar field components.

7.2.1 Reflector test methods

There are no specific standards for concentrating reflectors of solar thermal collectors. A group of experts in the field of optical mirror reflectance characterization has been working on a draft document of a reflectance measurement guideline. This group is part of the Task III: "Solar Technology and Advances Applications" from the SolarPACES (international cooperative network of CSP experts, IEA Implementing Agreement). The goal of Task III is to develop and promote such guidelines to become international standards through organizations like ISO, ASME, DIN, AENOR, ASTM etc.

Mirror reflectance measurement

The guideline for reflectance characterisation of solar reflectors was developed under the framework of a two year project "Development of guidelines for standards for concentrating solar power (CSP) components" within the SolarPACES and it can be downloaded from the following URL: http://www.solarpaces.org/Tasks/Task3/reflectance_guideline.htm. Other reference testing procedures can be found in the ASTM E 424 – 71 test methods which cover the measurement of solar energy transmittance and reflectance of materials in sheet form.

The solar reflectance measurements (ρ_s) can be performed using a spectroradiometer (method A) or a pyranometer (method B). With the method A, the reflectance is measured between 350 and 2500 nm wavelength range. The solar reflectance (ρ_s) is then calculated with normalized weighted ordinate energy intervals for the wavelength ordinates defined in the standards (ISO 9845-1 or ASTM G173), as follow:

$$\rho_S = \sum_{i=1}^{N} \rho(\lambda_i) E(\lambda_i) \Delta\lambda_i$$

Where $E(\lambda)\Delta\lambda_i$ are the normalized weighted energy values.

The standard ISO 9845-1 (Reference solar spectral irradiance at the ground at different receiving conditions) gives the spectral distribution of direct normal (with a 5,8º field-of-view angle) and hemispherical (on an equator-facing, 37º tilted plane with an albedo of 0,2) solar irradiance for air mass 1.5. This reference standard gives the solar energy weighted to calculate optical properties of materials (reflectance or transmittance). It does not give any procedure to measure those optical properties. The global and direct solar irradiance (G and G_b) values used for the determination of hemispheric spectral reflectance and the diffuse spectral reflectance and then, the specular spectral reflectance can be determined, which is the critical parameter for the reflector for concentrating collectors.

$$\rho_s(\lambda) = \rho_h(\lambda) - \rho_d(\lambda)$$

The lack of a specific standard for concentrating also leads to a wide range of durability/accelerated ageing test possibilities causing the following problems:

- Need to review a wide range of durability test standards from other technology fields to perform tailor-made durability tests which are adapted from several "selected" standards.
- Difficult to compare durability test results from different sources.
- No common definition for accelerated test exposure conditions that can differ significantly from service life conditions. Degradation factors need to be assessed.
- Validation of predicted service life through outdoor exposure tests or materials service life, where reliable test results are obtained, in most cases are only available once the new material is already in the market.

Table 1. Screening testing for solar reflectors[3]

Degradation mechanism	Critical periods of high environmental stress	Suitable accelerated test methods and range of degradation factors
Degradation of the protective layer	At high cumulative dose of solar irradiation, photooxidation, hydrolysis, acid rain	Weatherometer tests: ISO 4892 Plastics - Methods of exposure to laboratory light sources (UV, temperature and RH) Condensation test + irradiation SPART 14 - acid rain modification of SAE J1960, which is a weatherometer test ASTM G155-00ae1 Standard practice for operating xenon arc light apparatus for exposure of non-metallic materials
Corrosion of the reflecting layer	Under humidity conditions involving reflector	Salt spraying and hostile gases-SP method 2499 A, also corresponding to ISO/CD 21207 method A

[3] Task 27: Solar Building Facade Components: Final Report-Subtask B-Part2, International Energy Agency Solar Heating and Cooling Programme (2007).

Degradation mechanism	Critical periods of high environmental stress	Suitable accelerated test methods and range of degradation factors
	water condensation	
Surface abrasion	Wind, hail, cleaning	ASTM D4060-01 Standard Test Method for abrasion resistance of organic coatings by the taber abraser ISO 11998:1992 Paints and varnishes - determination of wetscrub resistance and cleanability of coatings
Surface soiling	Moisture, dust, dirt	ASTM D3274-95 Standard Test Method for evaluating degree of surface disfigurement of Paint Films by microbial (fungal or algal) growth or soil and dirt accumulation
Degradation of the substrate	Moisture, pollutants, acid rain, hail	Hail: ASTM E822-92(1996) Standard practice for determining resistance of Solar Collector covers to hail by impact with propelled ice balls ASTM E1038-98 Standard Test Method for determining resistance of Photovoltaic Modules to hail by impact with propelled ice balls
Loss of adhesion of protective coating	Moisture, pollutants, acid rain, hail, icing, UV, Thermal expansion	Hail: ASTM E822-92(1996) Standard practice for determining resistance of Solar Collector covers to hail by impact with propelled ice balls ASTM E1038-98 Standard Test Method for determining resistance of Photovoltaic Modules to hail by impact with propelled ice balls EN 12975-2 cap 5.10 Impact resistance test Icing: Build up of ice layers MIL-STD 810 E, Method 521 Icing /Freezing rain ISO 2653, ice formation, Test C Frost appearance IEC 60068-2-39,Z/AMD, combined sequential cold, low air pressure and damp heat test Thermal expansion: IEC 60068-2-14, Test N, Change of Temperature MIL-STD 810 E, Method 503.3, Temperature shock: ISO 10545 - Part 9 Ceramic tiles determination of resistance to thermal shock

7.2.2 Receiver test methods

The receiver of a concentrating collector is defined in the ISO 9488 as the part to which the solar radiation is finally directed or redirected, comprising the absorber and any associated glazing through which the radiation must pass.

Due to the commercial growth of CSP plants based on parabolic trough technology, the testing procedures for parabolic trough receivers (PTR) have been widely developed because the PTR is the key component for converting concentrated solar radiation into thermal energy in such CSP plants. Most of these testing procedures were elaborated for component research and development or manufacturing quality control, however they are not yet standardized even though some of them have been validated through Round Robin intercomparisons.

The main parameters for characterizing a PTR are the optical properties: solar transmittance of the glass envelope and solar absortance of the absorber tube which determine the PTR optical efficiency and the thermal properties: the thermal emittance of the absorber and the thermal losses curve at different absorber temperatures.

Optical characterization

The PTR optical characterization can be performed with two different procedures: destructive and non destructive measurement techniques. Destructive techniques use equipment for measuring the optical properties referred in the ASTM E 424-71[4] and are based on measuring small receiver samples. Among these technologies, the following ones can be highlighted:

- Reflectivity measurement equipment for UV-VIS-NIR able to measure with variable angles
- Fourier transforms far IR measurement equipment with accessories for measuring reflectance

Non destructive techniques allow measuring the optical properties of the entire PTR sample in a sequential way, and may be coupled with the thermal characterization or accelerated ageing tests. Recently several non destructive test methods with different testing approaches to determine the PTR optical properties have been developed in research centres like CENER[5], DLR[6] and NREL[7]. A Round Robin process will be performed in the near future in order to validate the different testing approaches.

Thermal characterization

Within CSP research and development activities several PTR thermal characterization procedures have been developed which can be performed with different testing approaches and complexity levels:

- Outdoor test procedures: usually performed on complete solar collector assembly (SCA) or test loops or collector module test platforms, by measuring the heat transfer fluid (HTF) flow and temperature difference between inlet and outlet to calculate the solar energy gain or the thermal losses (when the receiver is off-sun). The collector performance can be determined at steady state or quasi-dynamic conditions. As an overview the main outdoor testing facilities for parabolic trough collectors are:
    - Sandia Rotating Platform, AZTRAK test bench for a single parabolic trough collector module
    - CIEMAT-PSA Rotating Platform, KONTAS test bench for a parabolic trough collector module up to 20 m length and 6,8 m reflector aperture width
    - CIEMAT-PSA EuroTrough and SEGS Collector Test Loops
    - ENEA Solar collector test facility
    - DLR SOPRAN, Test bench for parabolic trough collectors with pressurized water
    - And several from CSP plant promoters

[4] American Standard ASTM E 424 – 71 "Standard Test Methods for Solar Energy Transmittance and Reflectance (Terrestrial) of Sheet Materials"

[5] E. Mateu et al. "Optical characterization test bench for parabolic trough receivers". SolarPACES 2011.

[6] J. Perpeintner et al. "Test benches for measurement of the optical efficiency of parabolic trough receivers using natural sunlight and solar simulator light". SolarPACES 2010.

[7] C. Kutscher et al. "Measuring the optical performance of evacuated receivers via an outdoor thermal transient test". SolarPACES 2011.

- Indoor test procedures: by using electrical heating elements[8] to characterize the thermal losses of the PTR at the same CSP plant operating temperatures. The goal of the test bench is to obtain the PTR thermal losses curve per unit length. Electrical power is supplied to the heating assemblies to maintain the absorber temperature. When a desired steady state temperature is reached, the measured electrical power equals the PTR heat losses. The thermal emittance of the absorber tube can be derived from the measured heat losses. As an overview the main indoor testing facilities for PTR thermal characterization are: CENER, DLR, NREL, Schott and others.

7.2.3 Accelerated ageing test procedures

Apart from the solar thermal collectors standards there are other existing durability standards which describe accelerated ageing test procedures that can be adapted for component durability assessment:

- The standard IEC 61701 applicable to photovoltaic (PV) modules specifies that the module ageing test shall be performed in a saline environment with a solution of 5% of sodium chloride at an ambient temperature of 35ºC, test length 96 hours.
- The standard for salt spray tests ISO 9227 (Corrosion tests in artificial atmospheres).

Also the IEC standards provide a description of the degradation factors due to environmental stresses in service conditions which need to be evaluated and measured to predict the expected component service life from the results of accelerating ageing tests. The general standard IEC 60721[9] can be used as a starting point; this standard contains recommendations for classifying stress severity for various climatic, mechanical, chemical, biological and electrical environments:

- IEC 60721-1 Classification of environmental parameters and their severity. Introduction to the standard.
- IEC 60721-2 Environmental conditions appearing in nature. Temperature and humidity, precipitation and wind, air pressure, solar radiation and temperature, dust, sand, salt mist/wind, earthquake vibrations and shocks, fauna and flora.
- IEC 60721-3 Classification of groups of environmental parameters and their severities. Storage, transportation, stationary use at weather protected locations, stationary use of non-weather protected locations, ground vehicle installations, ship environment, portable and non-stationary use.

Although some standards are applicable to photovoltaic (PV) modules, they could be also used for solar thermal collectors. The standard IEC 61215 is applicable to photovoltaic (PV) modules. The international standard IEC 62108 specifies the minimum requirements for the

[8] F. Burkholder and C. Kutscher, Heat-Loss Testing of Solel's UVAC3 Parabolic Trough Receiver. Technical Report NREL/TP-550-42394 January 2008.

[9] IEC 60721, Classification of Environmental Conditions, International Electrotechnical Commission, P.O. Box 131, CH - 1211 Geneva 20, Switzerland.

design qualification and type approval of concentrator photovoltaic (CPV) modules and assemblies suitable for long-term operation in general open-air climates as defined in IEC 60721-2-1. Those durability tests are similar to the standard IEC 61215 specific to photovoltaic modules.

8 TEXT PROPOSALS FOR STANDARD REVISION

This section summarizes 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.

8.1 Terms and definitions

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. (*Note: The section below is numbered as it is proposed for 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}

8.2 Test method and procedure

In order to adapt the existing test method and procedure within EN 12975 to be used for tracking and concentrating collectors the following paragraphs within chapter 6 of the current Standard have been modified or added as described below. (*Note: The section below is numbered as it is proposed for the new standard*.)

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 to 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 ±1°.
Non-imaging stationary collectors such as CPCs 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:

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

6. *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: 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 needs to be carried out with the tracking system supplied by the manufacturer.

8.3 Properties of water

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 in the current draft. (*Note: The section below is numbered as it is proposed for the new standard*.)

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*[10] $(0 \leq \vartheta \leq 99{,}6°C)$ *and at 12 bars*[11] $(100 \leq \vartheta \leq 185°C)$. *The water is assumed to be in liquid phase.*

$$\rho(\vartheta) = a_0 + a_1\vartheta + a_2\vartheta^2 + a_3\vartheta^3 + a_4\vartheta^4 + a_5\vartheta^5$$
$$(0 \leq \vartheta \leq 185°C)$$

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 $(0 \leq \vartheta \leq 99{,}6°C)$*) or 0,12% (compared to IAPWS* $(0 \leq \vartheta \leq 185°C)$*). 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.*

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 $(0 \leq \vartheta \leq 99{,}5°C)$ *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*[12] $(0 \leq \vartheta \leq 99{,}6°C)$ *and at 12 bars*[13] $(100 \leq \vartheta \leq 185°C)$. *The water is assumed to be in liquid phase.*

$$c_p(\vartheta) = a_0 + a_1\vartheta + a_2\vartheta^2 + a_3\vartheta^3 + a_4\vartheta^4 + a_5\vartheta^5 + a_6\vartheta^6$$
$$(0 \leq \vartheta \leq 185°C)$$

$a_0 =$ 4,2184

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

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

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

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

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

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

[11] 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

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

[13] 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

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

The deviation of the polynomial to the values from those references is always smaller than 0,04% (compared to VDI $(0 \leq \vartheta \leq 99{,}6°C)$*) or 0,14% (compared to IAPWS* $(0 \leq \vartheta \leq 185°C)$*). 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.*

9 PROPOSALS FOR FUTURE WORK

During the work related to performance testing of concentrating and tracking collectors new issues came up which are relevant for the solar thermal industry as well as for users of solar thermal collectors. This section lists and describes the most relevant issues to pave the way to future work items.

9.1 Cooperation between stakeholders of different technologies

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 to 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; each is 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 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 committee TC117 for Solar Thermal Electric has recently been created, and its work program was established during the kick-off meeting held on March 7th-8th 2012 in Madrid. During this meeting it was agreed that a close collaboration should take place between the new IEC/TC117 and the ISO/TC180, since both have concentrating/ tracking collectors and their components in their scopes.

Another common point between low/medium temperature and CSP applications is the new set of definitions developed within the QAIST project, which are included in the ISO/DIS 9806 standard. The new set of parameter definitions has also been agreed to 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 while still allowing for a fair comparison of thermal performance test results. Most of the definitions 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 (these are out of the scope of testing standards). This set of definitions will be included in the next revision of the ISO 9488 Solar Energy vocabulary in the near future.

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

9.2 Components

Methods on how to characterize important components of tracking and concentrating collectors such as reflector material, receivers and tracking systems are 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.

9.3 In-situ measurements

Increasing numbers of collector models are constructed in sizes which cannot be tested in a laboratory setting (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 that the energy output, the power and temperature levels of such innovative concepts can be accurately characterized, investors, manufacturers, planners/engineers and funding authorities are interested in independent measurements (third party measurements).

Basic performance measurements in these types of collector applications can be done according EN 12975-2. The method uses quasi-dynamic conditions to provide a physical model which covers most of the requirements and conditions of such collector applications, but additional work is required to:

- Improve and adapt the method to accommodate the 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
- Disseminate the methods to interested parties

Durability tests for innovative collector concepts may differ from 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 may need to be updated to take into account environmental impacts, regional requirements and additional requirements (e.g. corrosion, degradation by abrasion)

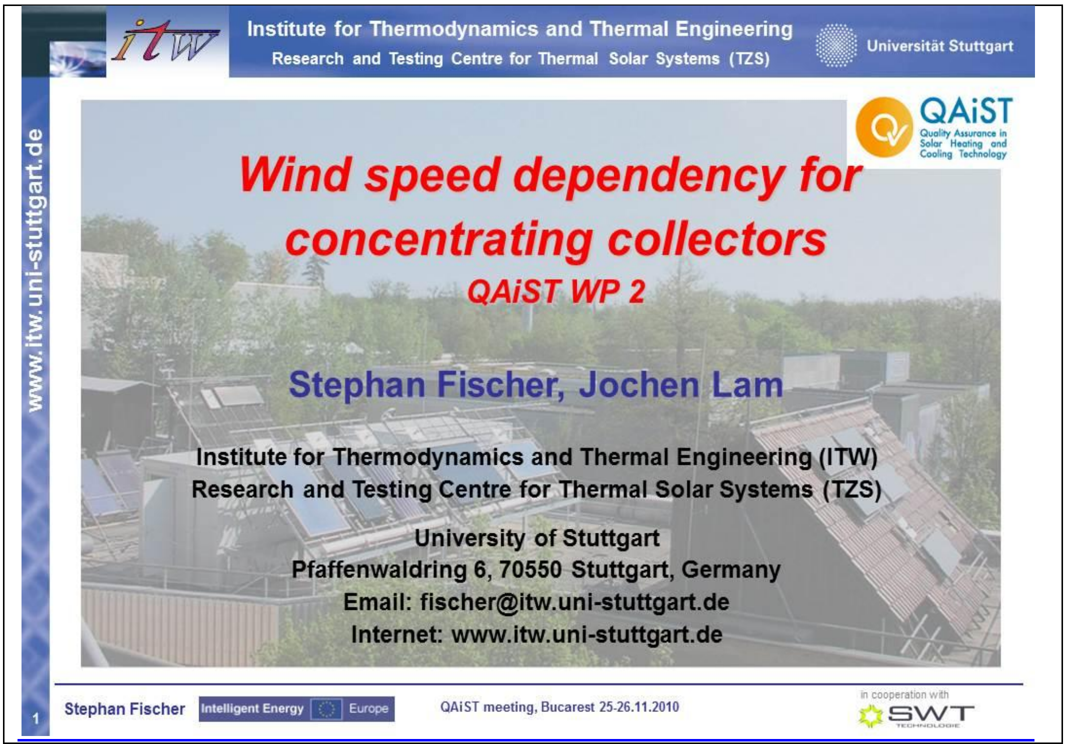
9.4 Round Robin testing up to 200°C

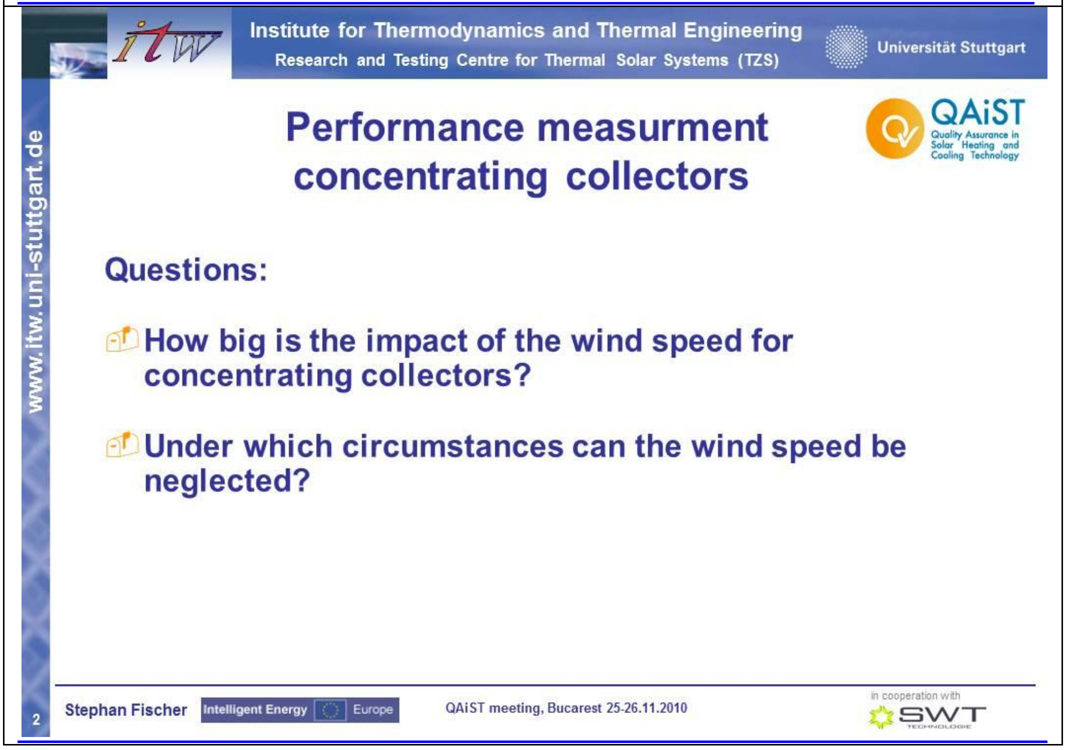
Test results must be accurate, reliable, repeatable and comparable. The round robin in QAiST showed that results of testing solar collectors and systems in a laboratory setting are accurate and comparable amongst European laboratories. New test issues are likely to arise for mid temperature range products, which will also face the benchmark set by the QAiST results. A round robin for performance measurements of innovative mid/high temperature collectors is an important 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, given the size and transportation logistics of mid/high temperature collectors. Administration of this task by an independent body like IfEP (Germany) was very helpful in the past, and should be continued. A procedure for a mid/high temperature round robin should be developed, taking into account the temperature levels and special heat transfer fluids associated with mid/high temperature collectors.

9.5 Phase change liquids

The solar thermal industry is increasingly focusing on industrial process heat applications. Saturated steam is a common and widespread medium to transfer heat in industrial processes. Concentrating and tracking collectors are capable of producing the required steam for industrial processes. However, current standards do not cover phase change liquids such as evaporated water or the resulting two-phase flow conditions. Future work should include performance modeling and testing with two-phase flow and saturated steam in order to address this important need.

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





Institute for Thermodynamics and Thermal Engineering
Research and Testing Centre for Thermal Solar Systems (TZS)
Universität Stuttgart

QAiST Quality Assurance in Solar Heating and Cooling Technology

www.itw.uni-stuttgart.de

Performance measurment concentrating collectors

Approach:

- Calculation of the heat loss for a receiver tube
  - without cladding tube
  - with cladding tube
  - with evacuated cladding tube
- Calculation of the power curves for different concentration ratios
- Comparison with a standard flat plate collector

3 Stephan Fischer | Intelligent Energy Europe | QAiST meeting, Bucarest 25-26.11.2010 | in cooperation with SWT

Institute for Thermodynamics and Thermal Engineering
Research and Testing Centre for Thermal Solar Systems (TZS)
Universität Stuttgart

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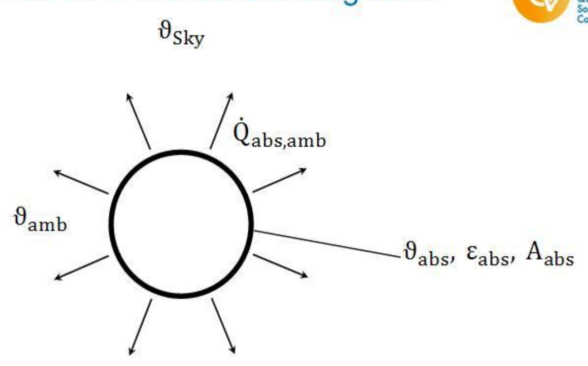
Heat Loss without cladding tube



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

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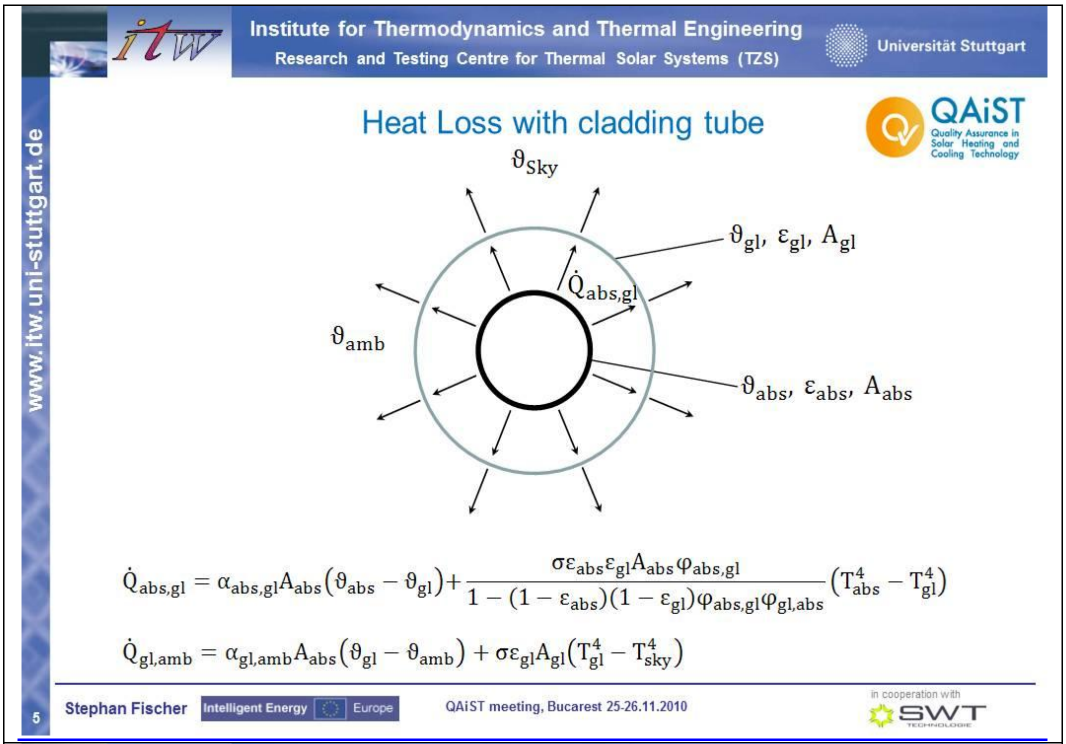
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Heat Loss with cladding tube
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ϑ_{Sky}
$\vartheta_{gl}, \varepsilon_{gl}, A_{gl}$
$\dot{Q}_{abs,gl}$
ϑ_{amb}
$\vartheta_{abs}, \varepsilon_{abs}, A_{abs}$
$\dot{Q}_{abs,gl} = \alpha_{abs,gl} A_{abs} (\vartheta_{abs} - \vartheta_{gl}) + \frac{\sigma \varepsilon_{abs} \varepsilon_{gl} A_{abs} \varphi_{abs,gl}}{1 - (1 - \varepsilon_{abs})(1 - \varepsilon_{gl}) \varphi_{abs,gl} \varphi_{gl,abs}} (T_{abs}^4 - T_{gl}^4)$
$\dot{Q}_{gl,amb} = \alpha_{gl,amb} A_{abs} (\vartheta_{gl} - \vartheta_{amb}) + \sigma \varepsilon_{gl} A_{gl} (T_{gl}^4 - T_{sky}^4)$
5
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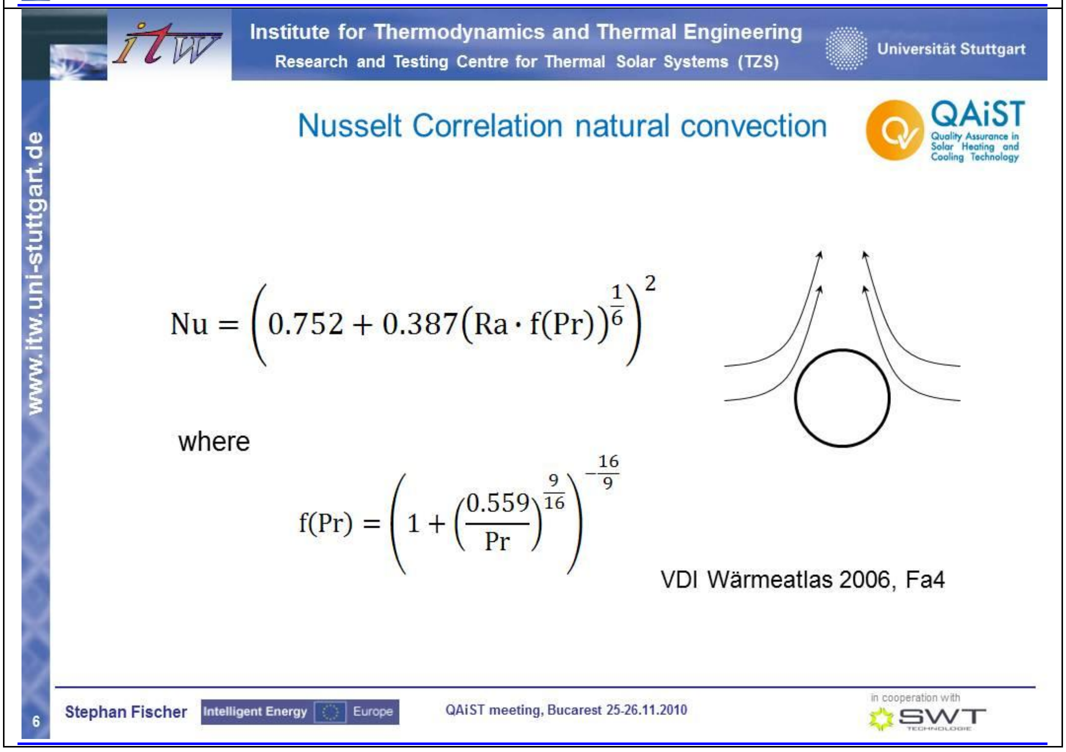
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Nusselt Correlation natural convection
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$Nu = \left(0.752 + 0.387 (Ra \cdot f(Pr))^{\frac{1}{6}}\right)^2$
where
$f(Pr) = \left(1 + \left(\frac{0.559}{Pr}\right)^{\frac{9}{16}}\right)^{-\frac{16}{9}}$
VDI Wärmeatlas 2006, Fa4
6
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Nusselt correlation forced convection

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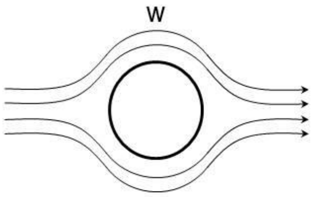
$$Nu = 0.3 + \sqrt{Nu_{lam}{}^2 + Nu_{tur}{}^2}$$



where

$$Nu_{lam} = 0.664\,\sqrt{Re}\,\sqrt[3]{Pr}$$

$$Nu_{tur} = \frac{0.037\,Re^{0.8}\,Pr}{1 + 2.443\,Re^{-0.1}\,(Pr^{2/3} - 1)}$$

VDI Wärmeatlas 2006, Gf1

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Nusselt correlation for annulus

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

$\text{if } 10^2 < GrPr < 10^4$:

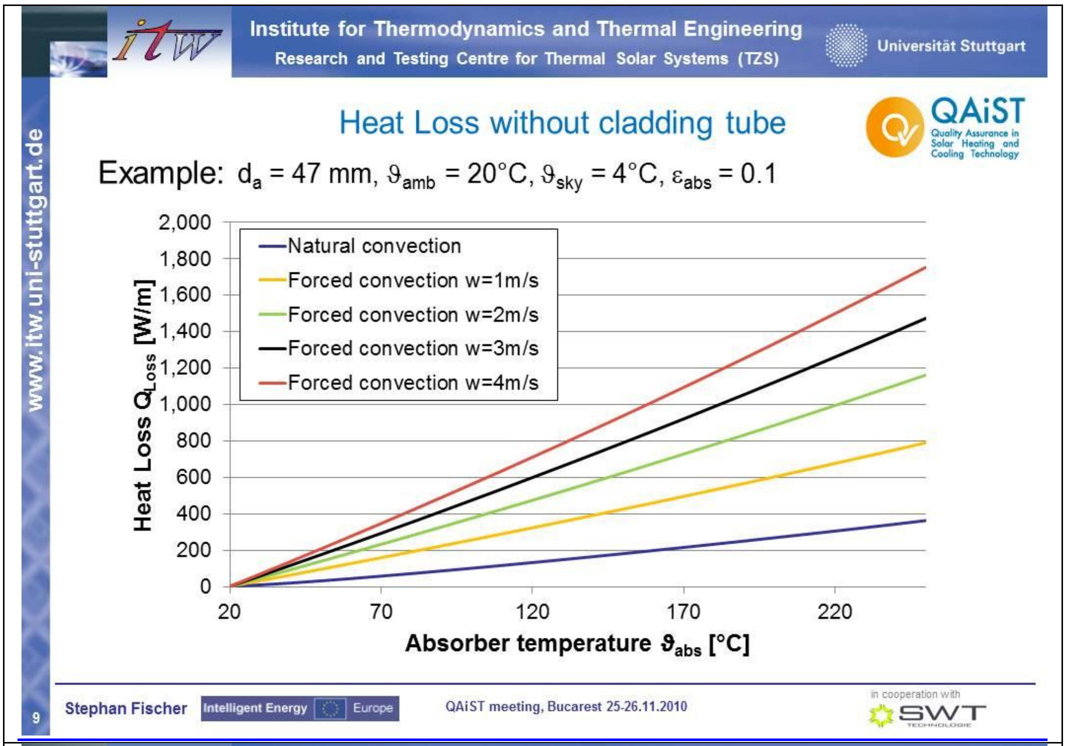
$$Nu = 1 + 0.54 \cdot 10^{-4} GrPr + 1{,}482 \cdot 10^{-8} (GrPr)^2 + 1{,}021 \cdot 10^{-12} (GrPr)^3$$

$\text{if } GrPr < 10^2$: $\quad Nu = 1$

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
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Example: d_a = 47 mm, ϑ_amb = 20°C, ϑ_sky = 4°C, ε_abs = 0.1
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]
2,000
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
20
70
120
170
220
Absorber temperature ϑ_abs [°C]
9
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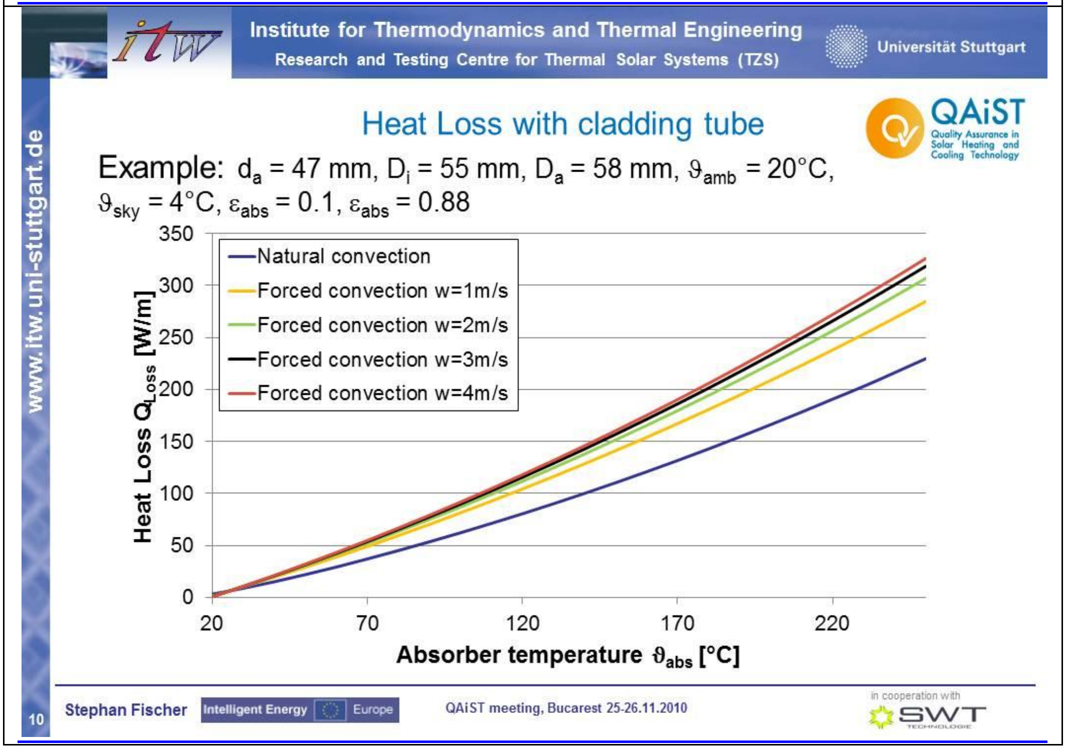
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Heat Loss with cladding tube
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Example: d_a = 47 mm, D_i = 55 mm, D_a = 58 mm, ϑ_amb = 20°C,
ϑ_sky = 4°C, ε_abs = 0.1, ε_abs = 0.88
Natural convection
Forced convection w=1m/s
Forced convection w=2m/s
Forced convection w=3m/s
Forced convection w=4m/s
Heat Loss Q_Loss [W/m]
350
300
250
200
150
100
50
0
20
70
120
170
220
Absorber temperature ϑ_abs [°C]
10
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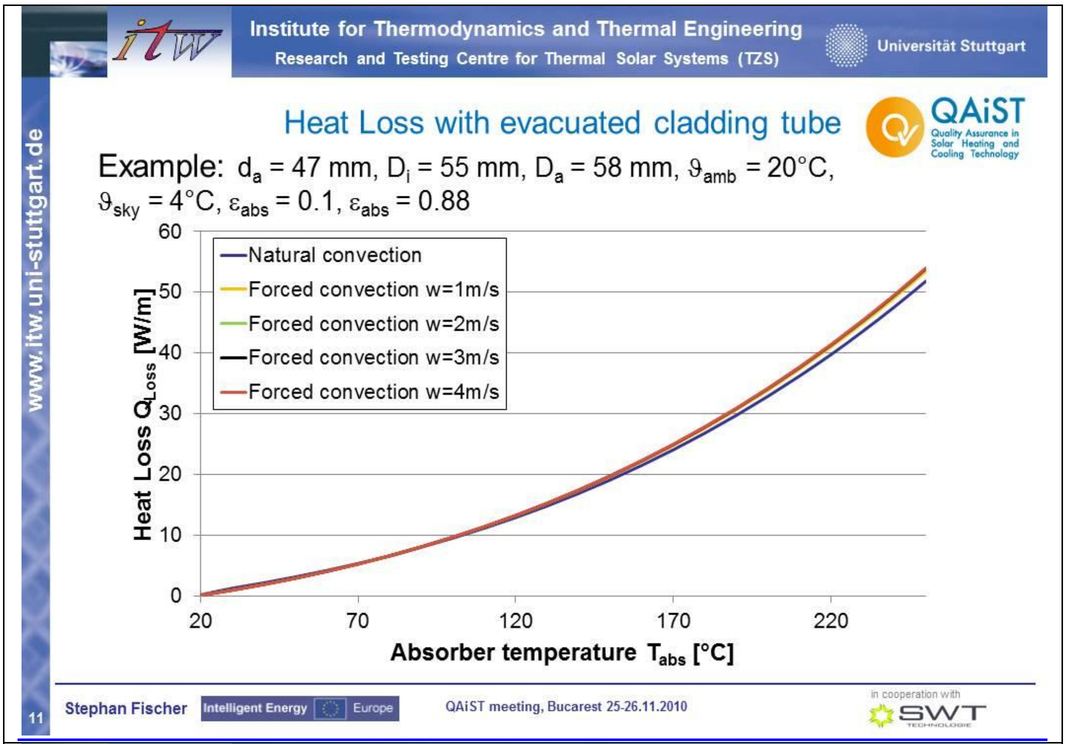
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Heat Loss with evacuated cladding tube
QAiST
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Example: d_a = 47 mm, D_i = 55 mm, D_a = 58 mm, ϑ_{amb} = 20°C, ϑ_{sky} = 4°C, ε_{abs} = 0.1, ε_{abs} = 0.88
Natural convection
Forced convection w=1m/s
Forced convection w=2m/s
Forced convection w=3m/s
Forced convection w=4m/s
Heat Loss Q_{Loss} [W/m]
0
10
20
30
40
50
60
20
70
120
170
220
Absorber temperature T_{abs} [°C]
11
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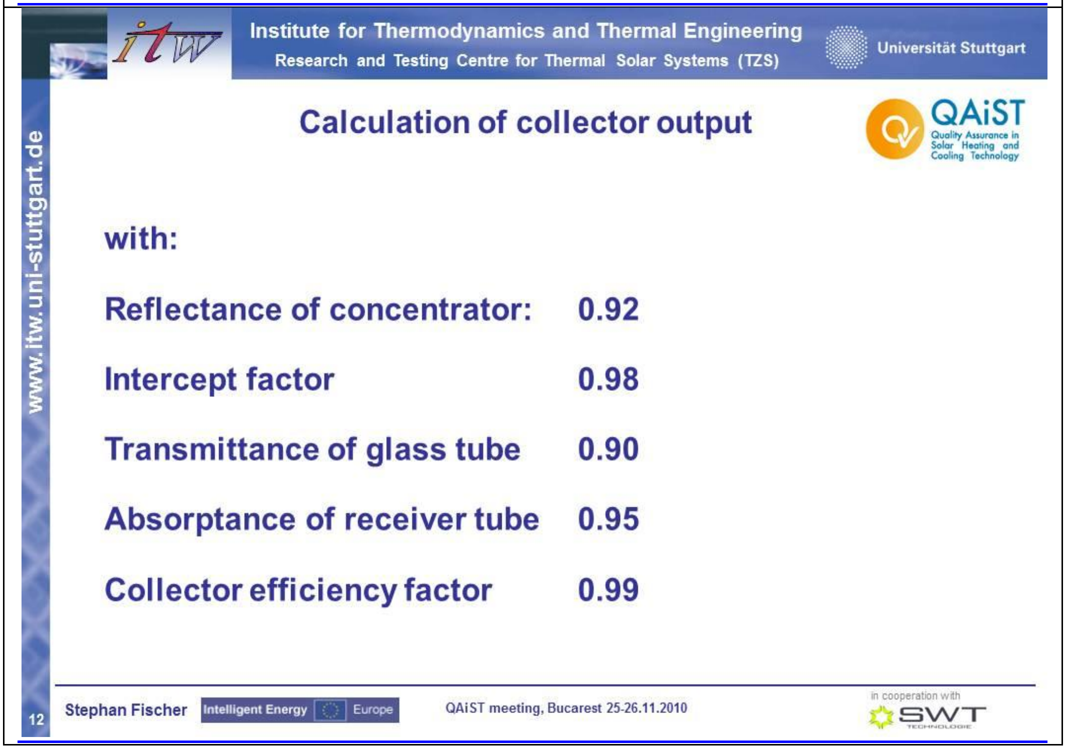
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Calculation of collector output
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with:
Reflectance of concentrator: 0.92
Intercept factor 0.98
Transmittance of glass tube 0.90
Absorptance of receiver tube 0.95
Collector efficiency factor 0.99
12
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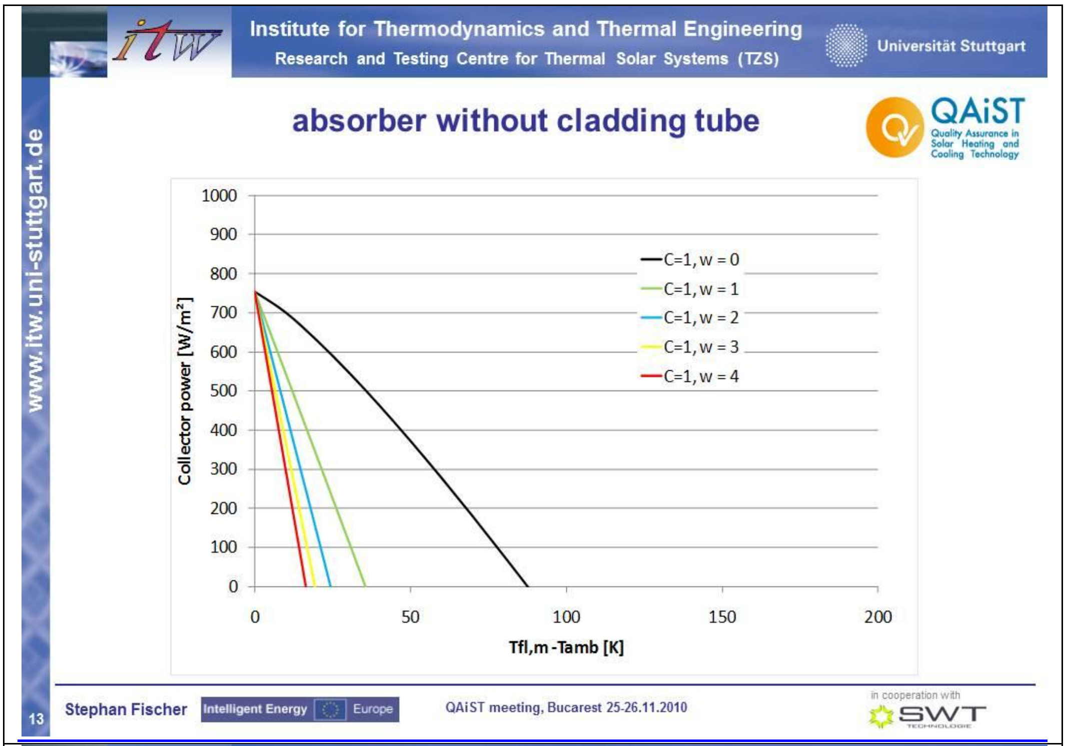
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absorber without cladding tube
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Collector power [W/m²]
Tfl,m-Tamb [K]
C=1, w = 0
C=1, w = 1
C=1, w = 2
C=1, w = 3
C=1, w = 4
13
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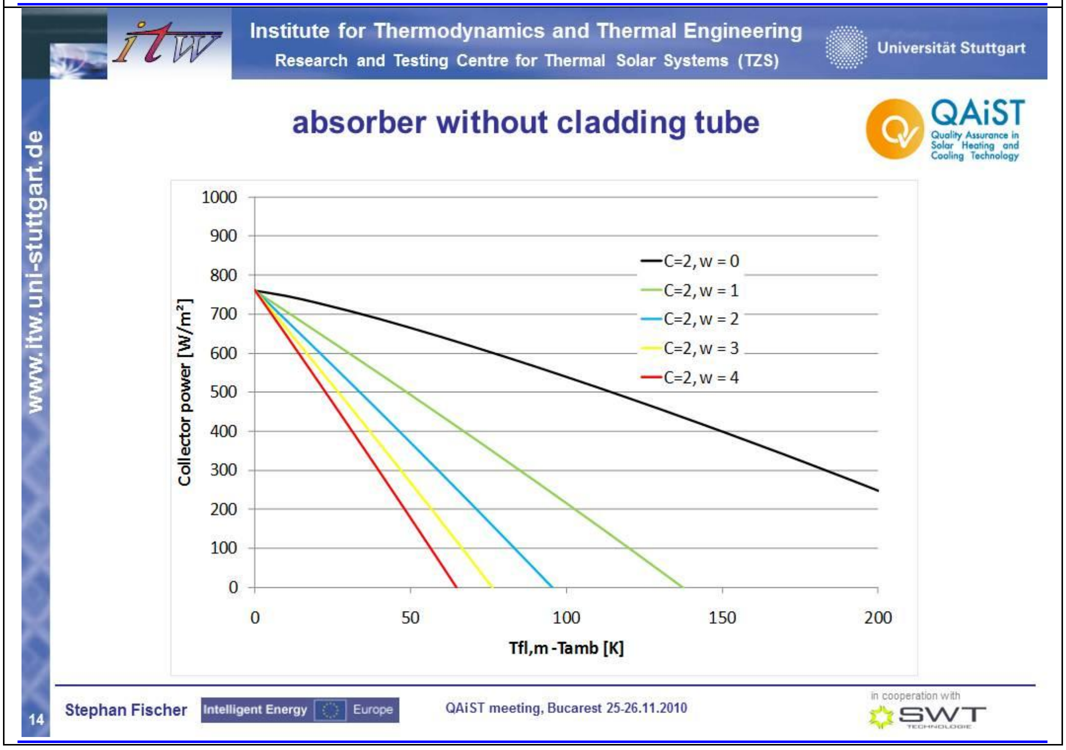
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Collector power [W/m²]
Tfl,m-Tamb [K]
C=2, w = 0
C=2, w = 1
C=2, w = 2
C=2, w = 3
C=2, w = 4
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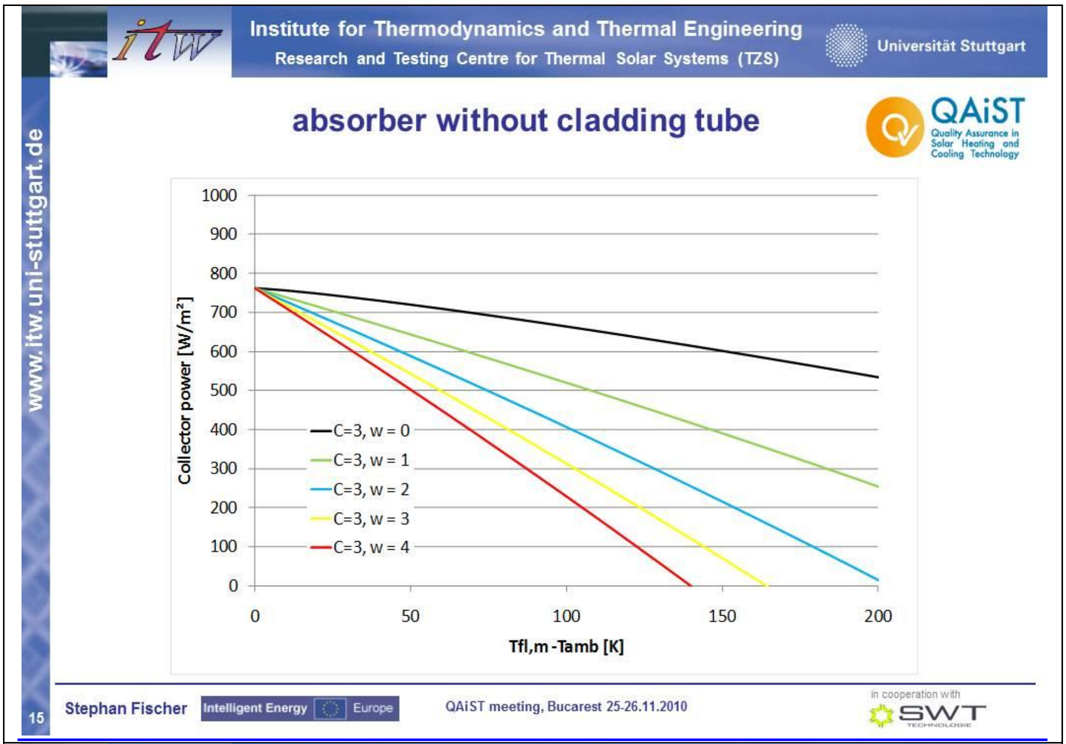
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Collector power [W/m²]
Tfl,m -Tamb [K]
C=3, w = 0
C=3, w = 1
C=3, w = 2
C=3, w = 3
C=3, w = 4
15
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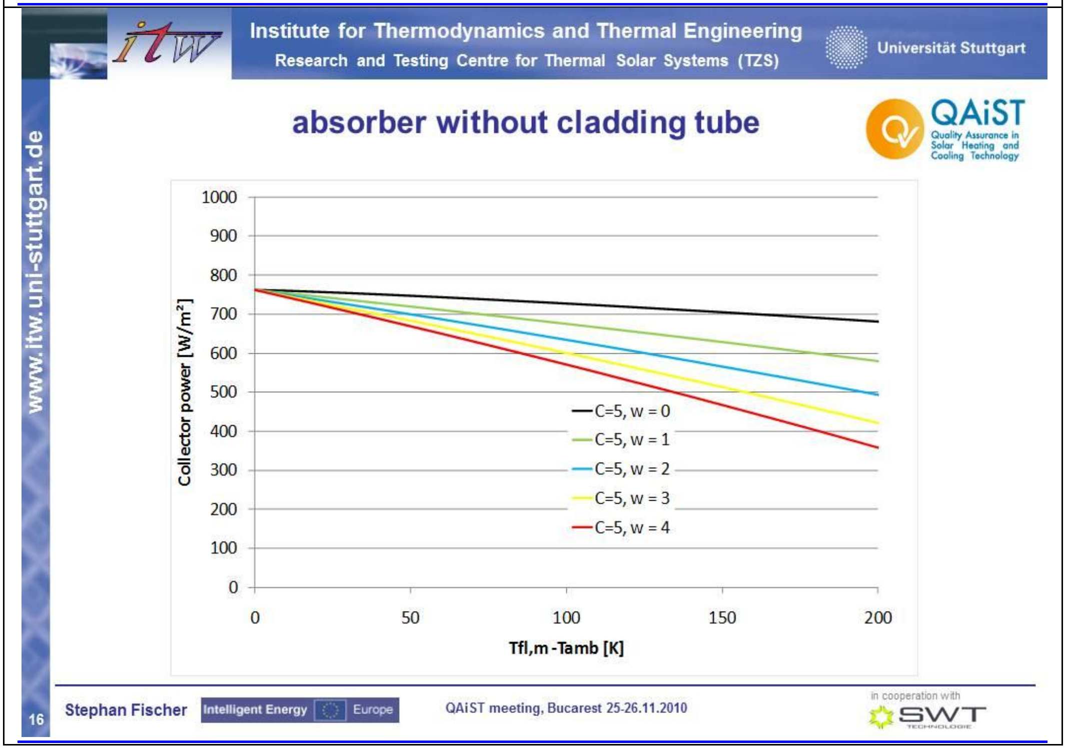
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Collector power [W/m²]
Tfl,m -Tamb [K]
C=5, w = 0
C=5, w = 1
C=5, w = 2
C=5, w = 3
C=5, w = 4
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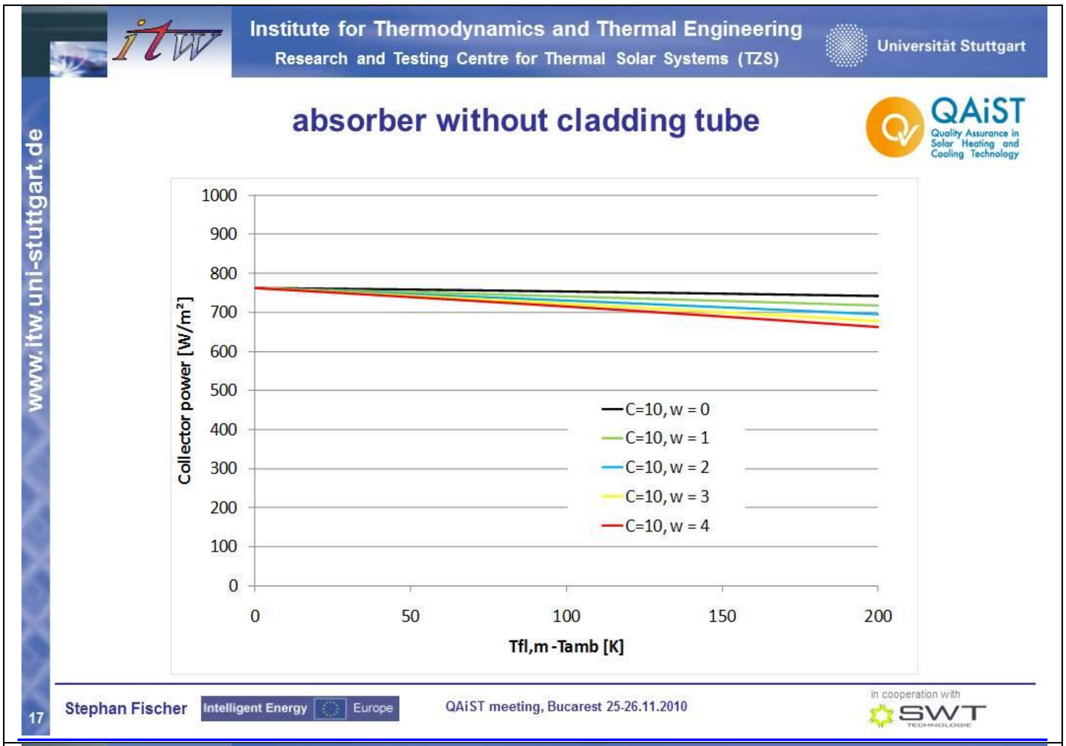
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absorber without cladding tube
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1000
900
800
700
600
500
400
300
200
100
0
Collector power [W/m²]
0
50
100
150
200
Tfl,m -Tamb [K]
C=10, w = 0
C=10, w = 1
C=10, w = 2
C=10, w = 3
C=10, w = 4
17
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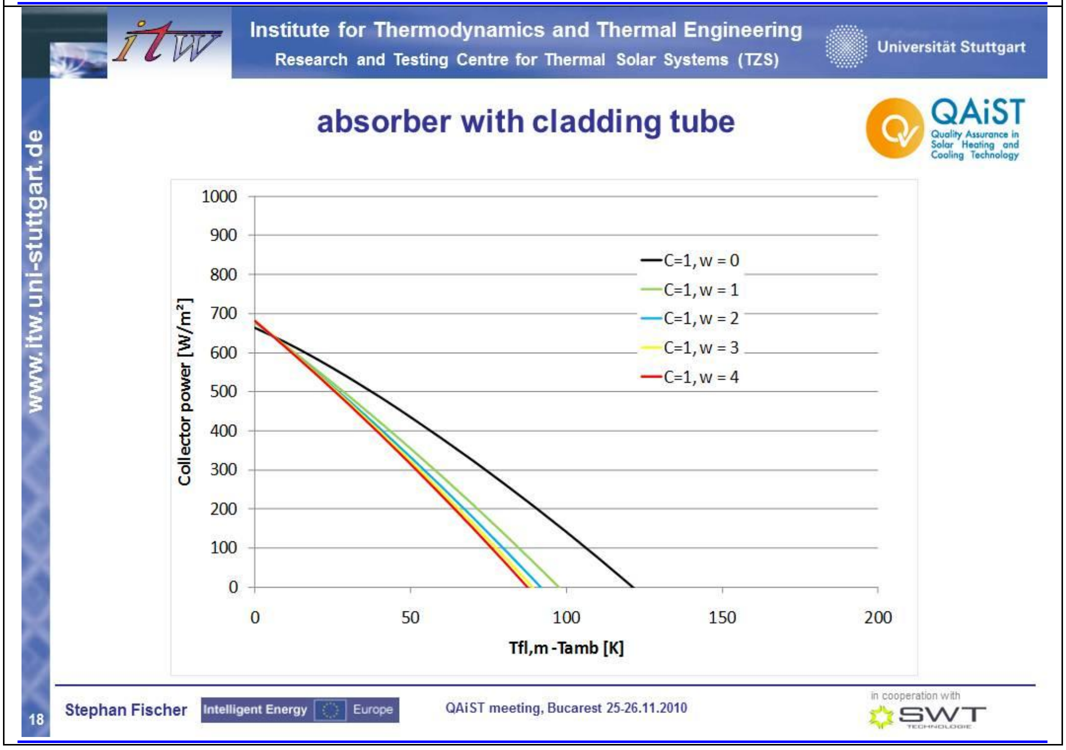
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Collector power [W/m²]
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200
Tfl,m -Tamb [K]
C=1, w = 0
C=1, w = 1
C=1, w = 2
C=1, w = 3
C=1, w = 4
18
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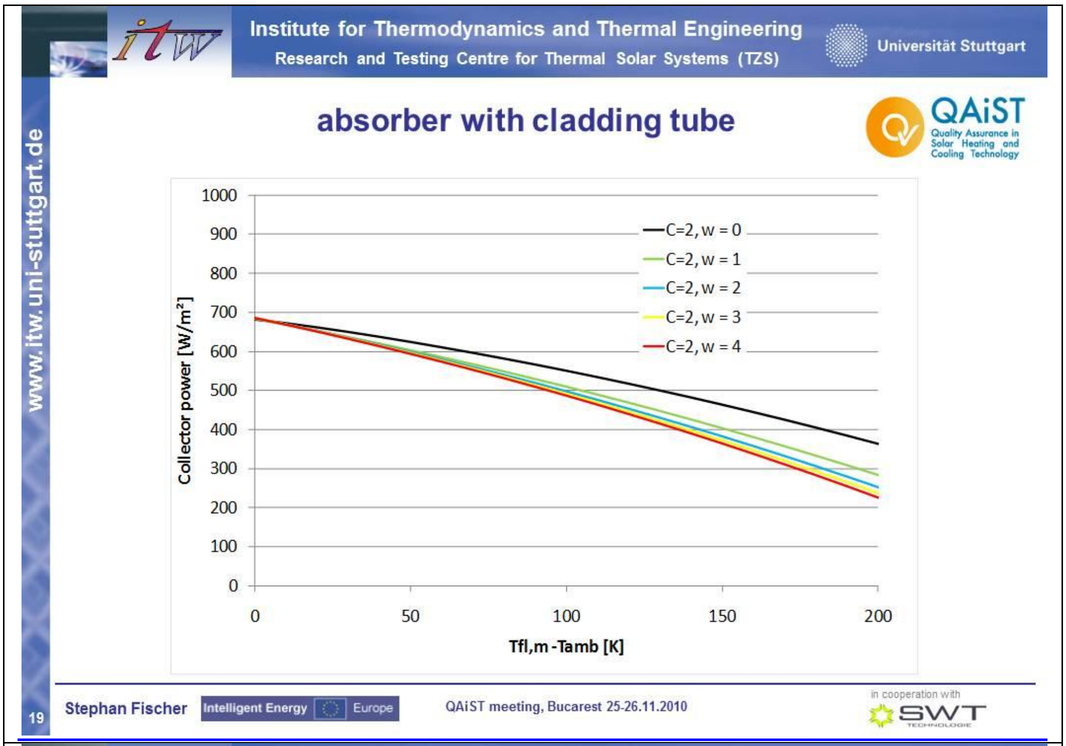
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Collector power [W/m²]
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200
Tfl,m -Tamb [K]
C=2, w = 0
C=2, w = 1
C=2, w = 2
C=2, w = 3
C=2, w = 4
19
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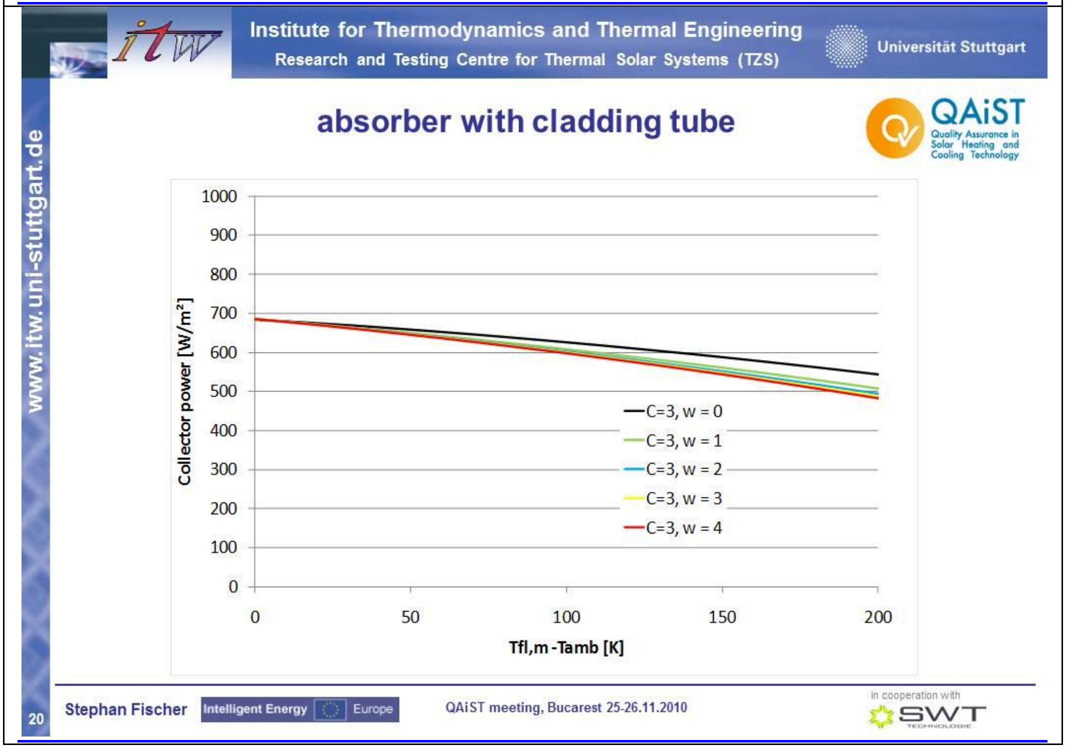
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absorber with cladding tube
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1000
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0
Collector power [W/m²]
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200
Tfl,m -Tamb [K]
C=3, w = 0
C=3, w = 1
C=3, w = 2
C=3, w = 3
C=3, w = 4
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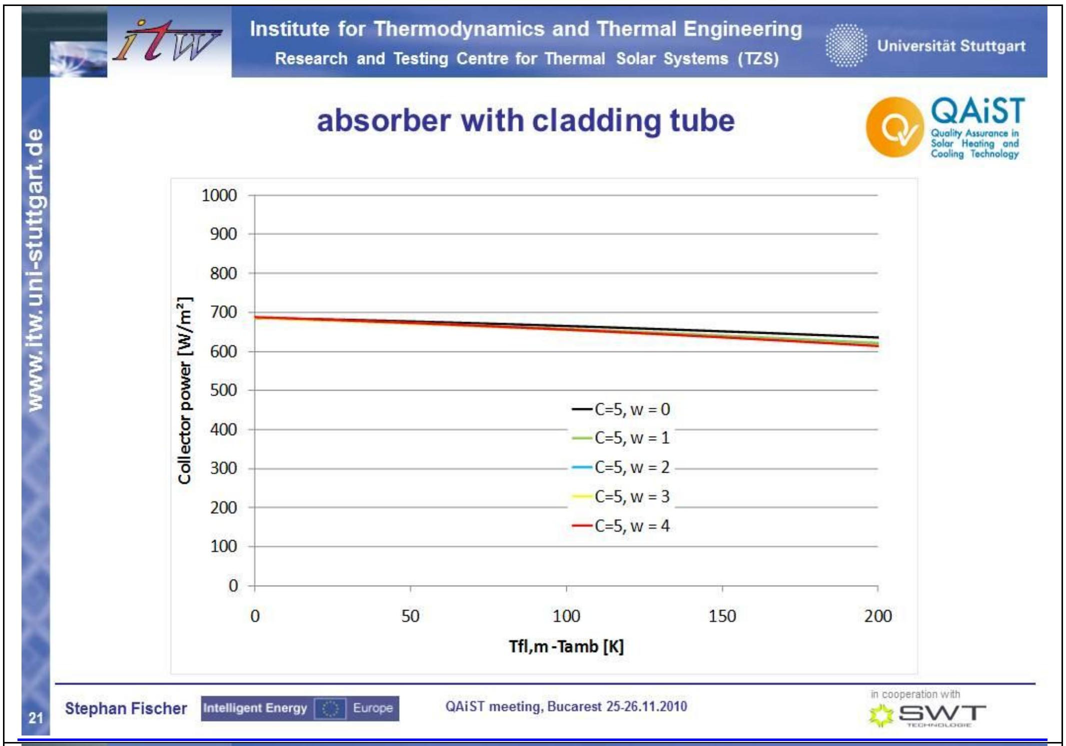
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Collector power [W/m²]
Tfl,m -Tamb [K]
C=5, w = 0
C=5, w = 1
C=5, w = 2
C=5, w = 3
C=5, w = 4
21
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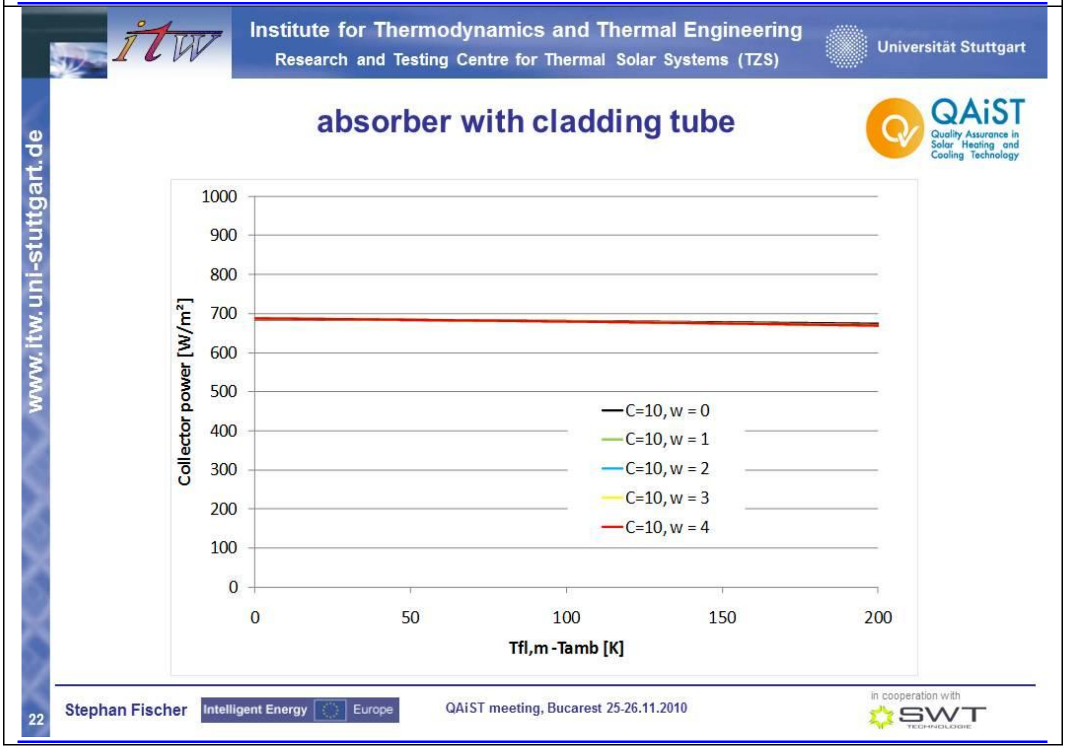
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Collector power [W/m²]
Tfl,m -Tamb [K]
C=10, w = 0
C=10, w = 1
C=10, w = 2
C=10, w = 3
C=10, w = 4
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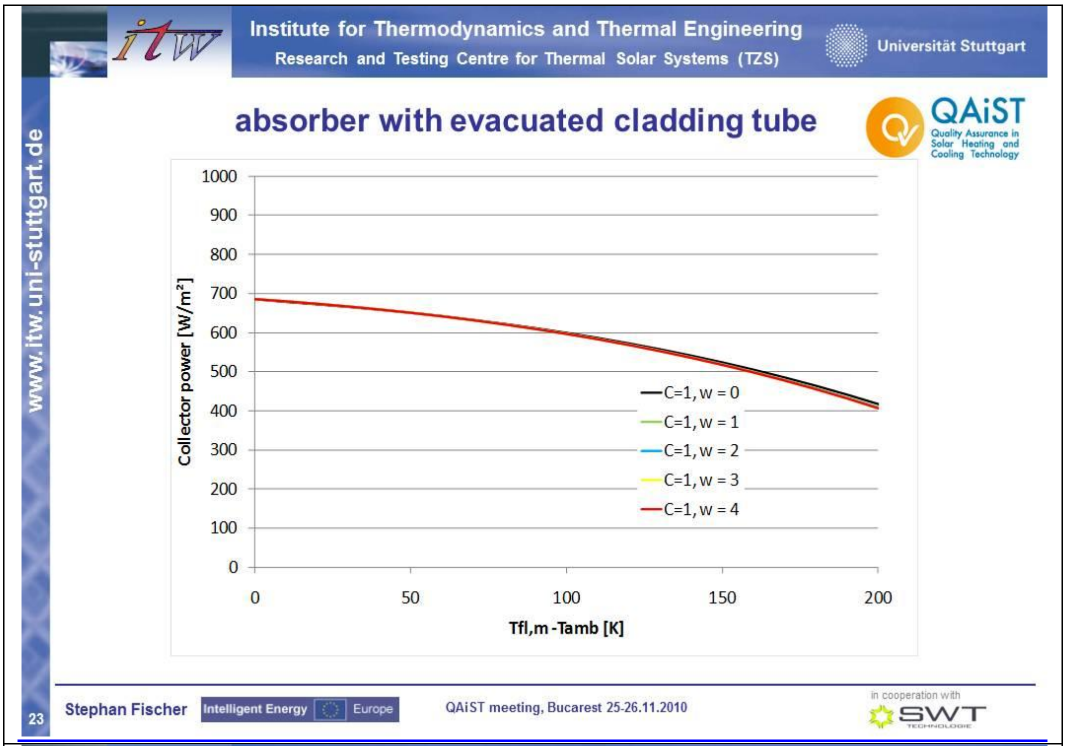
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absorber with evacuated cladding tube
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Collector power [W/m²]
1000
900
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300
200
100
0
0
50
100
150
200
Tfl,m-Tamb [K]
C=1, w = 0
C=1, w = 1
C=1, w = 2
C=1, w = 3
C=1, w = 4
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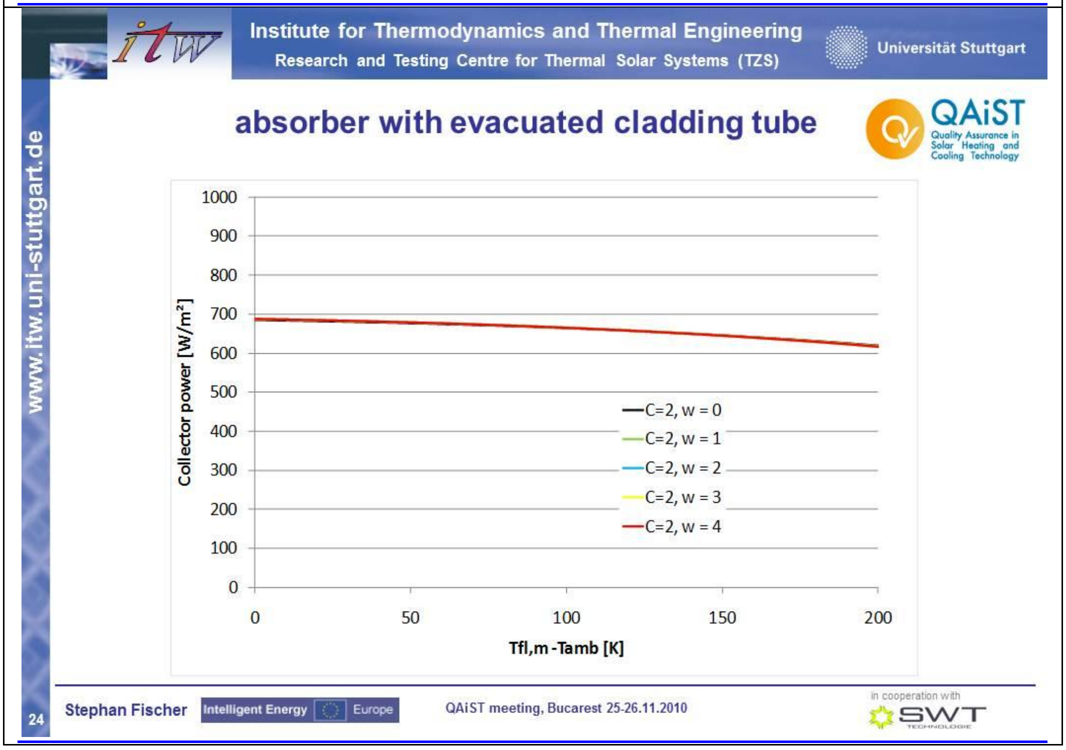
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Collector power [W/m²]
1000
900
800
700
600
500
400
300
200
100
0
0
50
100
150
200
Tfl,m-Tamb [K]
C=2, w = 0
C=2, w = 1
C=2, w = 2
C=2, w = 3
C=2, w = 4
24
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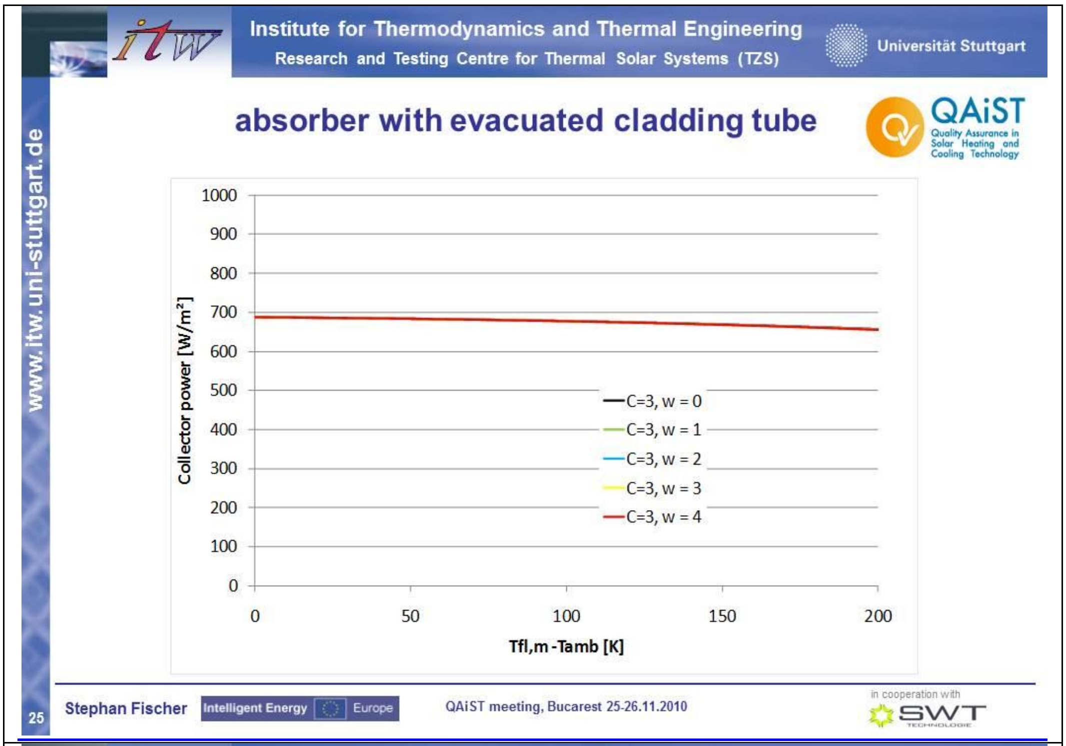
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Collector power [W/m²]
Tfl,m-Tamb [K]
C=3, w = 0
C=3, w = 1
C=3, w = 2
C=3, w = 3
C=3, w = 4
25
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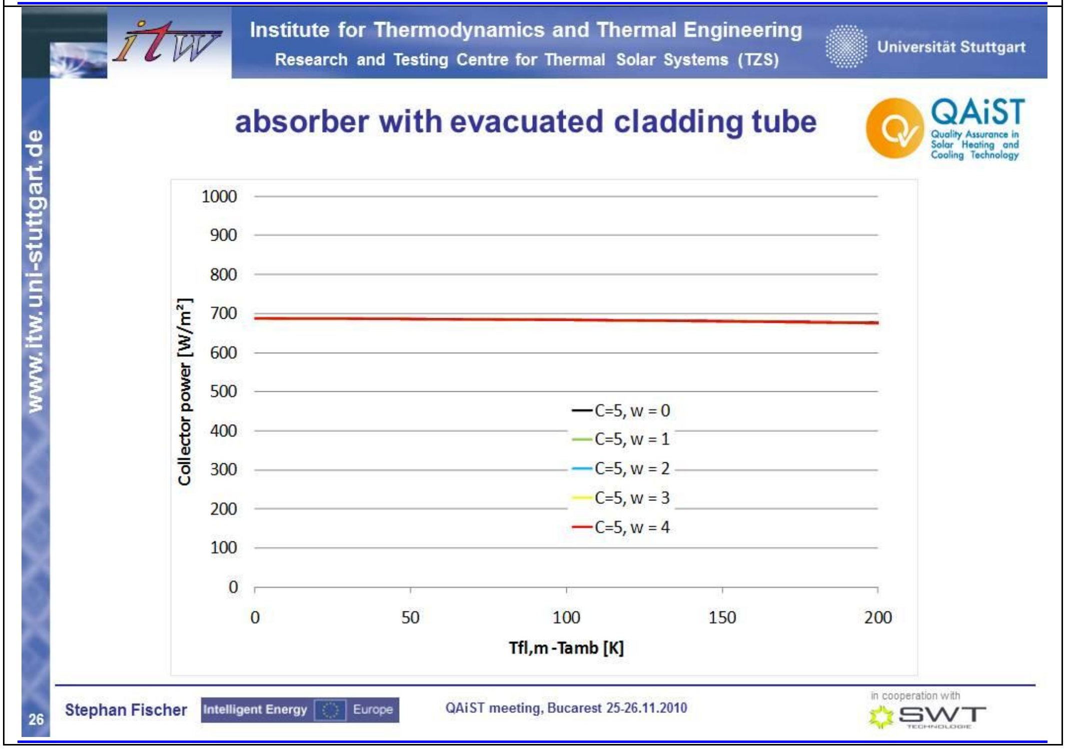
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Collector power [W/m²]
Tfl,m-Tamb [K]
C=5, w = 0
C=5, w = 1
C=5, w = 2
C=5, w = 3
C=5, w = 4
26
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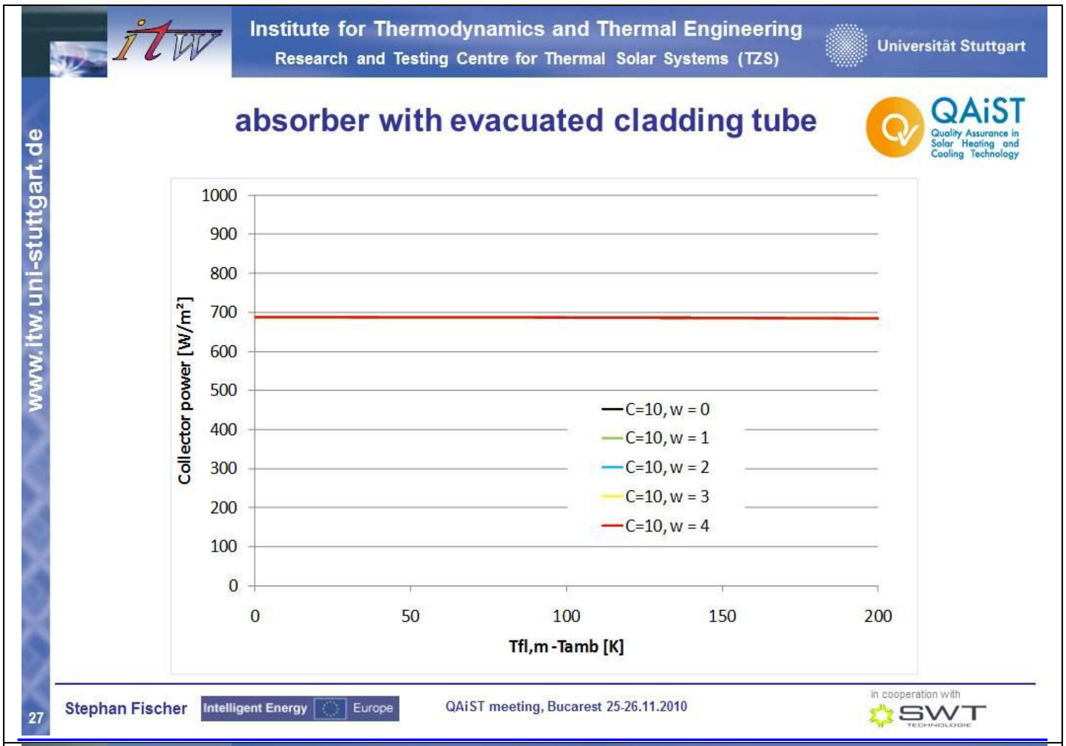
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absorber with evacuated cladding tube
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Collector power [W/m²]
Tfl,m -Tamb [K]
C=10, w = 0
C=10, w = 1
C=10, w = 2
C=10, w = 3
C=10, w = 4
27
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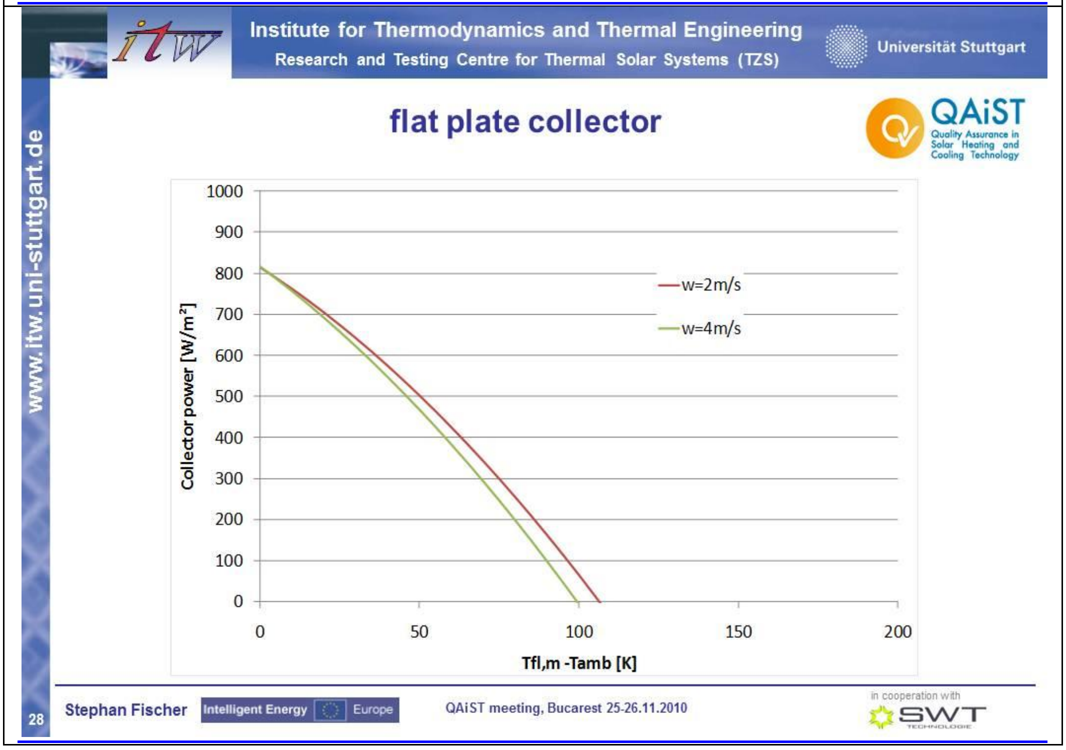
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flat plate collector
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Quality Assurance in Solar Heating and Cooling Technology
Collector power [W/m²]
Tfl,m -Tamb [K]
w=2m/s
w=4m/s
28
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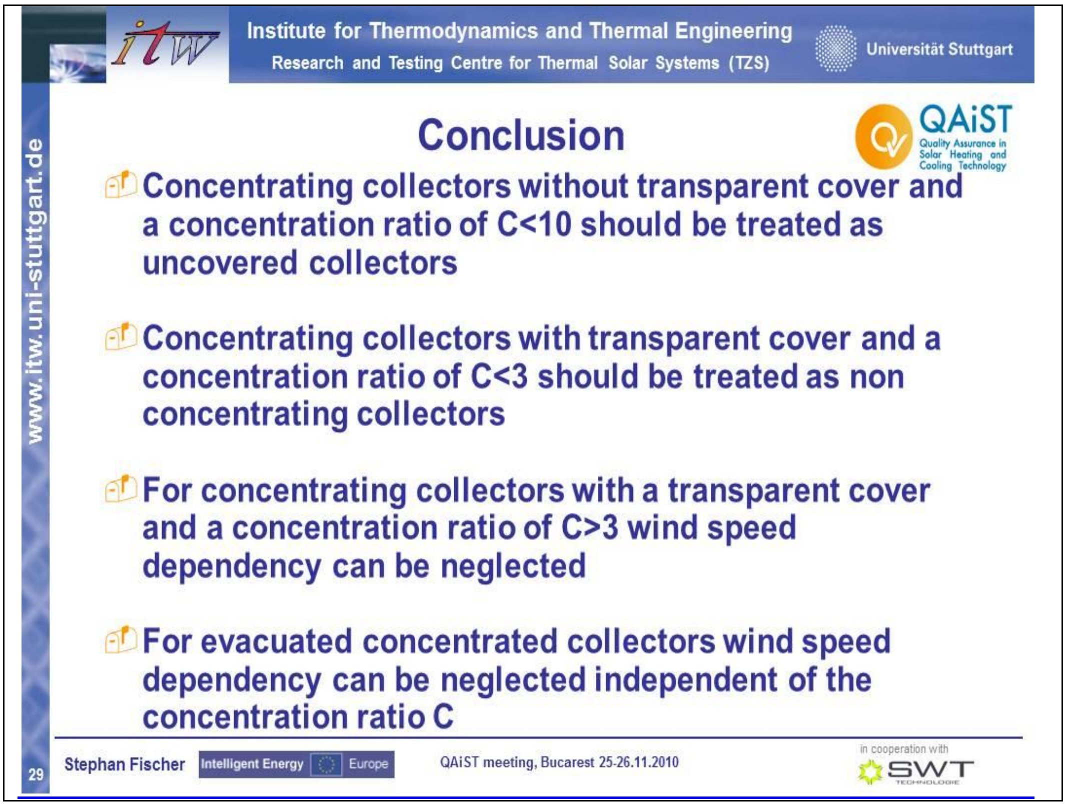
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Conclusion
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Concentrating collectors without transparent cover and a concentration ratio of C<10 should be treated as uncovered collectors
Concentrating collectors with transparent cover and a concentration 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

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ISFH

Performance tests up to higher fluid temperatures

Carsten Lampe,
Daniel Eggert,
Maik Kirchner,
Philipp Schwarzbach

Nov. 2010

Institut für Solarenergieforschung Hameln

Leibniz Universität Hannover

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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

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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QAiST Quality Assurance in Solar Heating and Cooling Technology

Hurdles

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- 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

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- 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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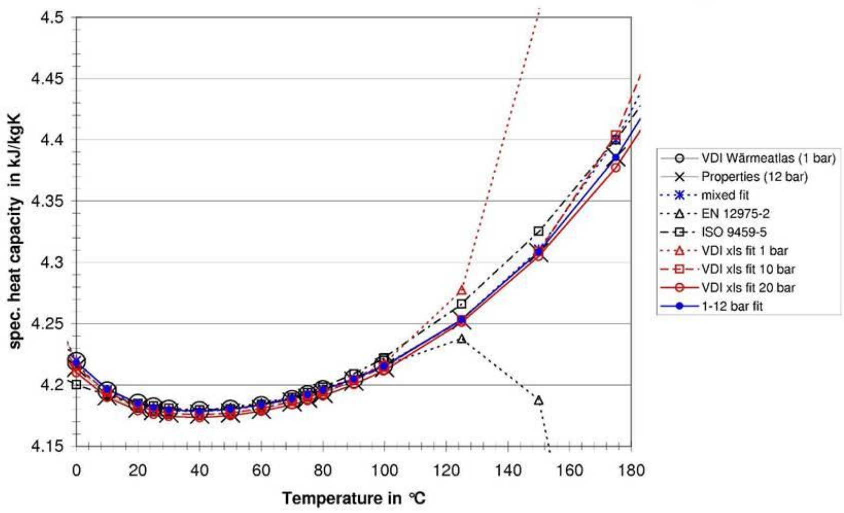

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State of works

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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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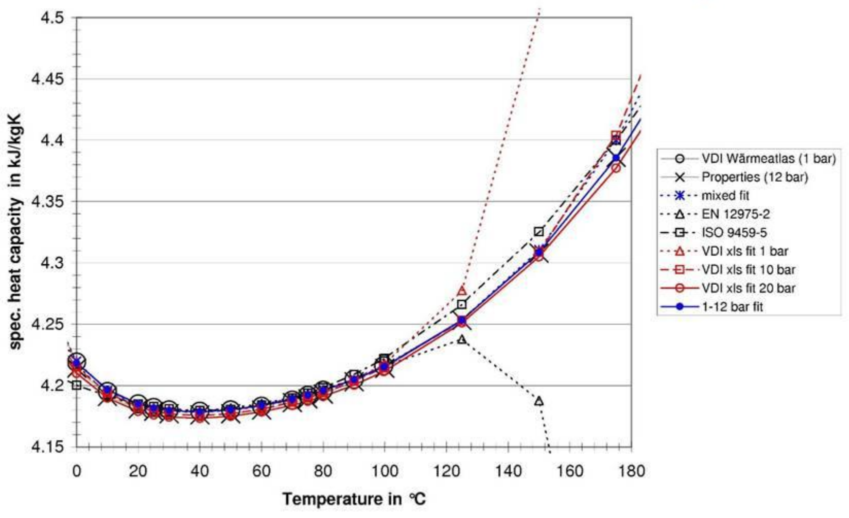
State of works



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State of works

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

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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Next steps

Check different fits for density

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