INDOOR SYSTEM TESTING
BASED ON ISO-9459-5 USING A DYNAMIC SOLAR SIMULATOR

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1. Introduction

In order to enable indoor testing of solar thermal systems the international standard ISO 9459-5:2007 has to be adapted to indoor test conditions. If a system test is performed with the Dynamic System Test Method (DST-method) according to ISO 9459-5:2007, the measured data are evaluated by using the InSitu Software ISS (Spirkl, 1997). The characteristic system parameters derived by this process are used for the long term performance prediction (LTP) to determine the solar fraction f_{sol} of the system. As a basis for performing indoor tests it is necessary to define appropriate artificial radiation profiles. To do this, artificially generated "measured data", so called "synthetic data" were used. This synthetic data was generated by means of TRNSYS simulations and evaluated with the InSitu Software ISS according to the procedure specified in ISO 9459-5:2007. Using different sets of data as input data for the TRNSYS model, different system answers and thus different LTPs were obtained. This effect is well known from outdoor measurements with the same system under different weather conditions. According to Naron and Ree (1999) the observed maximum deviation in the solar fraction due to different weather conditions is ± 5 % relative. This paper describes the newly developed dynamic solar simulator and presents an indoor system test procedure on the basis of ISO 9459-5: 2007.

2. Background

The increasing number of new products of the European solar thermal industry is leading to a growing demand for tests of collectors and solar thermal systems. Due to the limited testing capacity caused by the Central European weather conditions, especially during the winter period, the realisation of short development times remains a key problem. With respect to the European objectives for climate protection and reduction of fossil fuel demand this situation is unsatisfying. Hence new solutions for accelerated tests and an enlargement of the test capacities of the European research and testing institutes are required.

In order to overcome this obstacle a new dynamic solar simulator has been developed and constructed at ITW. Its lamp array consists of 14 metal halide lamps and enables testing of solar collectors and systems with a total collector area up to 10 m². In a distance of 2 m from the lamp array the homogeneity of the irradiance distribution is ± 12 %. A spectrum similar to the hemispherical irradiance specified in CIE 85-1989 Tab. 4 (1989), AM 1.5 G is achieved.

One major innovation of the dynamic solar simulator is the computer controlled variation of the irradiance. By a combination of electronic dimming of the lamps and a mechanical shading device, user-defined irradiance levels from below 100 W m^{-2} to nearly 1200 W m^{-2} can be achieved in a reproducible way. Hence it is worldwide for the first time possible to expose collectors and solar thermal systems to realistically varied computer controlled solar irradiance profiles during an indoor test.

3. Technical specifications of the dynamic solar simulator

The key component of the dynamic solar simulator is the lamp array with its accessories, consisting of 14 metal halide lamps in combination with a special filter glass array, the so called "cold sky" and the shading-device. The tilt angle of the lamp array can be adjusted from 0° (horizontal) to 70°. To ensure constant ambient conditions the solar simulator is located in a climate chamber which is 9 m long, 6 m wide and 5.1 m high. The temperature inside the climate chamber can be set between 10°C and 30°C. The complete test area is 3.7 m wide and 2.7 m high. This area of almost 10 m² is large enough to test either several collectors in parallel or one complete solar thermal system.

A sketch of the new solar simulator, consisting of the collector support rig with temperature control unit and lamp array with cold sky situated in a climate chamber, is shown in Fig. 1. The temperature control unit is used to supply the collector test samples, or store respectively, with water at different temperatures needed according to the corresponding test procedures. To check the intensity and homogeneity of irradiance in the test area a moveable pyranometer situated on the xy-scanner is used before every measurement. The test area of the collector support rig can be set to tilt angles from 0° (horizontal) to 60°. This allows testing of thermosiphon systems mounted on the manufactures support frame as well as any other systems designed for sloped roof installations.

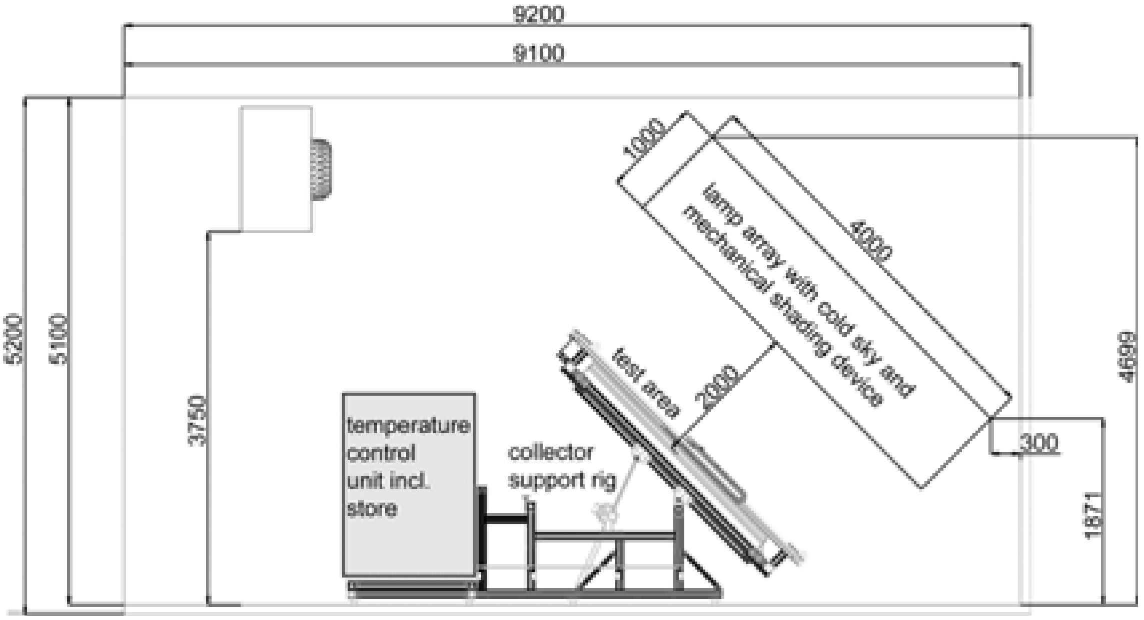

Fig. 1: Arrangement of the solar simulator within the climate chamber; collector support rig, temperature control unit, test area and lamp array

In contrast to the sun the lamp array produces thermal radiation to a larger extend which has to be blocked from the test area. This problem is solved by a “cold sky”. In this solar simulator a novel construction of a cold sky is used. It is split into 3 tracks. Each of the tracks is composed of two solar glass panels with a gap in-between. Cold air provided by a chiller is circulated through the gap cooling the glass panels.

The cold sky is directly connected to the lamps in such a way that it moves together with the lamp array when the tilt angle is changed. In Fig. 2 the solar simulator is shown in operation, the 3 tracks of the cold sky can be seen in front of the lamps. This placement of the cold sky close to the lamps allows the use of thin glass panels of small dimensions which results in a comparatively light construction. Furthermore the relatively thin glass panels only absorb a small amount of radiation leading to an increased efficiency of the solar simulator. Special glass, having the same transmittance for the whole solar spectrum is used. The temperature of the cold sky can be constantly kept close to ambient temperature even while the simulator is operated at maximum power.

Fig. 2: View of the solar simulator. At the back: Lamp array with cold sky. In the foreground: collector support rig with three collectors and hot water store on the right

The collectors and systems are mounted on a moveable collector support rig (in the foreground of Fig. 2). This wagon can be moved outside the climate chamber to mount the collectors or systems respectively. Since the temperature control unit is part of the support rig, all hydraulic connections can be done outside. Furthermore the xy-scanner is situated on the collector support wagon.

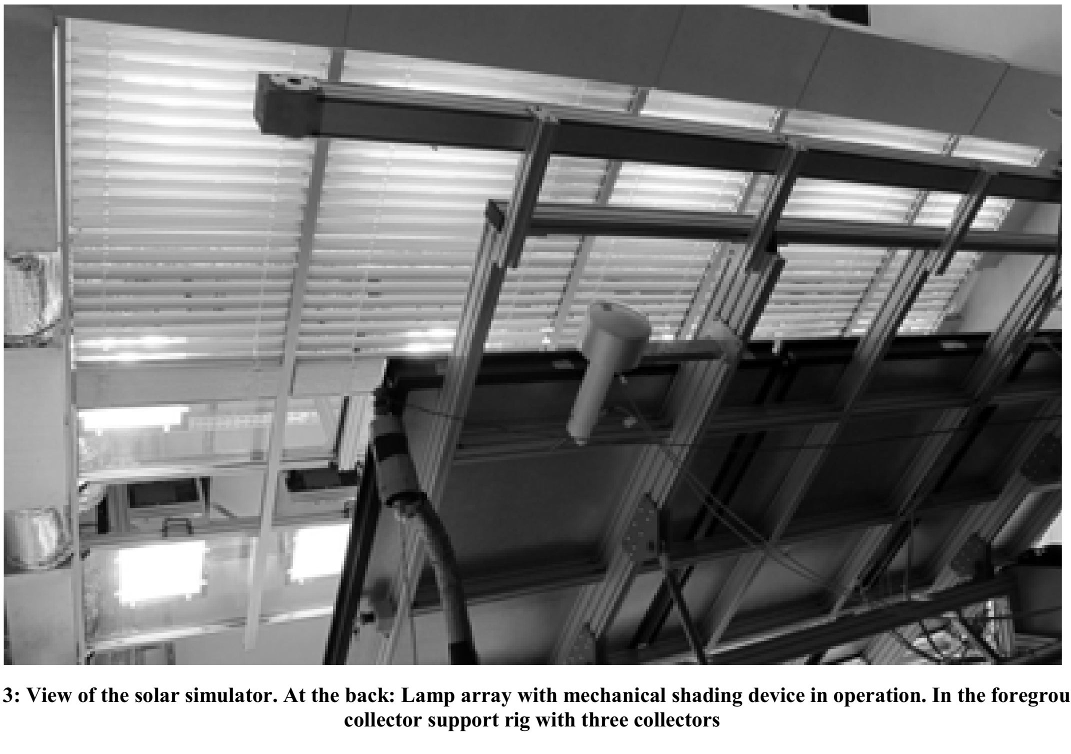

Fig. 3: View of the solar simulator. At the back: Lamp array with mechanical shading device in operation. In the foreground: collector support rig with three collectors

One major innovation of the dynamic solar simulator is the computer controlled variation of the irradiance. By a combination of electronic dimming of the lamps and a mechanical shading device, user-defined irradiance levels from below 100 W m^{-2} to nearly 1200 W m^{-2} can be achieved in a reproducible way. Fig. 3 shows the simulator with the just reeling-out mechanical shading device. In the range from 1200 W m^{-2} to 700 W m^{-2} the lamps are dimmed electronically. Further dimming leads to an inacceptable change in the spectrum of the lamps. Hence, to generate values beneath 700 W m^{-2} a mechanical shading device is used (see Fig. 3). It consists of several fins which can be set in different angles.

The lamps can be dimmed in 5 % steps (relative to the maximum power) in which the irradiance decreases linear. The fins can be moved in 5° steps between 0° and 65°. Position "65°" means completely open, i.e. the fins are standing in a right angle towards the lamp array. Hence the maximum radiation can pass through. In position "0°" the fins are fully closed and almost no radiation can pass through any more. In Fig. 4 the mean irradiance on the test area depending on electrical and mechanical shading effects is depicted. By using a computerised control system irradiance profiles in discrete steps of approximately 50 W m^{-2} can be created in a reproducible way. Hence it is for the first time possible to apply dynamic irradiance profiles of a whole day inside an indoor solar simulator.

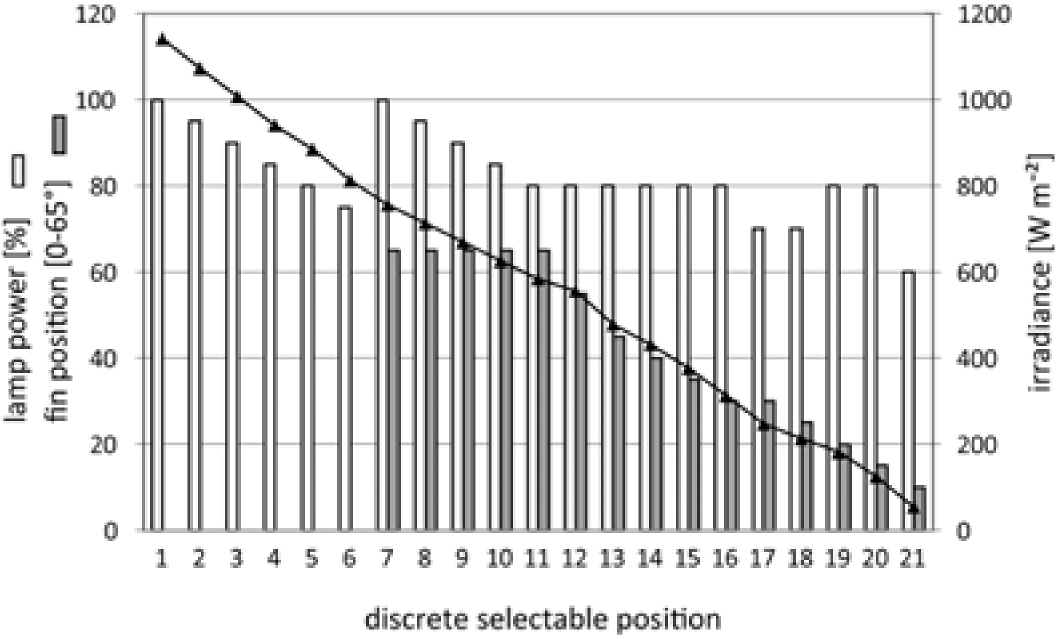

Fig. 4: Resulting irradiance (mean value) on the test area depending on electrical and mechanical shading effects

As dimming and shading has an effect on the spectrum of the lamps, spectral analyses where performed. In Fig. 5 a spectral analysis at 1000 W m^{-2} hemispherical irradiance is depicted. Additionally shown in Fig 5 is the reference spectrum at air mass (AM) 1.5. The measurement and the reference AM 1.5 differ, but are still in the acceptable range as defined in DIN V 4757-4: 1995[1].

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[1] DIN V 4757-4: 1995 is substituted since 2001 by DIN EN 12975 part 1 and 2. However, no other normative reference for solar thermal systems is known in which an interval of tolerance for the spectral distribution of solar simulators is defined.

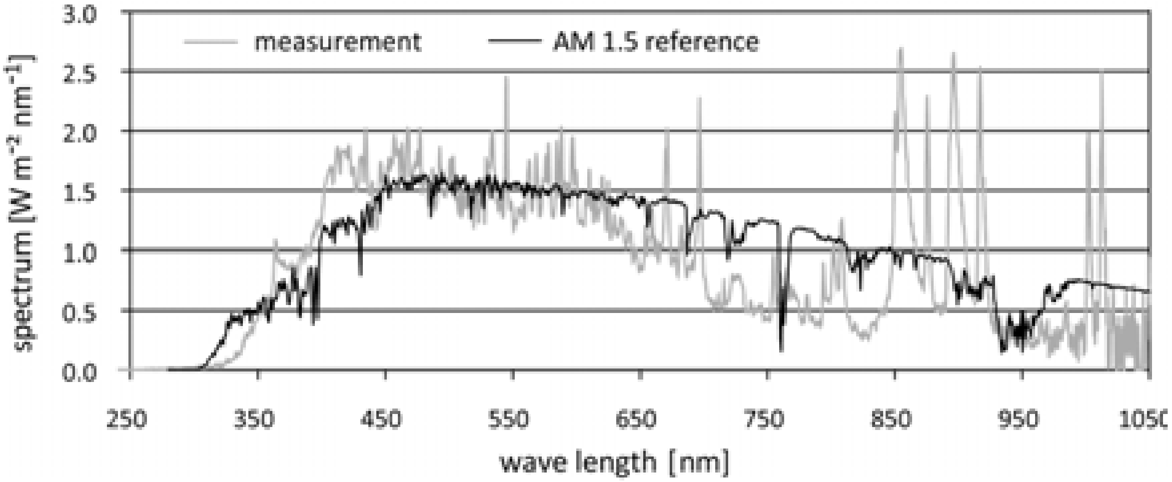

Fig. 5: Comparison of the spectra: measurement at 1000 W m^{-2} hemispherical irradiance and AM 1.5 reference according to CIE 85 (1989)

Further measurements where done to determine the influence of dimming the lamp power (LP) and mechanical shading (MS) on the spectrum. The results are depicted in Tab. 1. Dimming the lamps increases the UV-fraction between 0 and 400 nm. Down to a relative lamp power of 60 %, the change in the spectrum is still in the acceptable range of DIN V 4757-4: 1995[1] as shown in Tab. 1. Further dimming leads to an inacceptable high UV-fraction of the spectrum, as shown for a relative lamp power of 50 % with no mechanical shading (grey coloured fields). In contrast to the electrical dimming of the lamps, the mechanical shading increases the near IR-fraction. The change in the spectrum is small and in interval of tolerance. Thus it can be stated that all 21 discrete settings shown in Fig. 4 are within the exactable range required by DIN V 4757-4: 1995[1].

Tab. 1: Relative spectral distribution in dependency of the relative lamp power (LP) and mechanical shading (MS).

Wave length [nm]	**DIN V 4757-4[1] min...max** [%]	**LP 100 MS -** [%]	**LP 80 MS -** [%]	**LP 50 MS -** [%]	**LP 100 MS 65°** [%]	**LP 100 MS 40°** [%]	**LP 100 MS 10°** [%]
0-400	0...8	3.8	5.3	9.7	3.8	2.7	1.4
400-700	30...60	43.6	44.5	43.6	41.4	39.5	45.7
700-1000	18...40	22.8	18.9	14.7	19.2	19.6	21.2
1000-2500	15...45	29.7	31.3	32.0	35.6	38.3	31.6
Irradiance [W m^{-2}]	1000 1000	1150	884	510	756	634	110

In Fig. 6 the homogeneity distribution of the irradiance in a distance of 2 m of the lamp array is shown. The irradiance on the Z axis is depicted versus the location on the test area, which is shown on the X- and Y- axis starting in the upper left corner of the test area. It deviates ± 12 % from the mean value of 1135 W m^{-2}. This is even better than the value of ± 15 % required by the EN 12975-2: 2006. The two minima in the x-y-axis direction are caused by the strut section of the cold sky and the mechanical shading (see also Fig. 3).

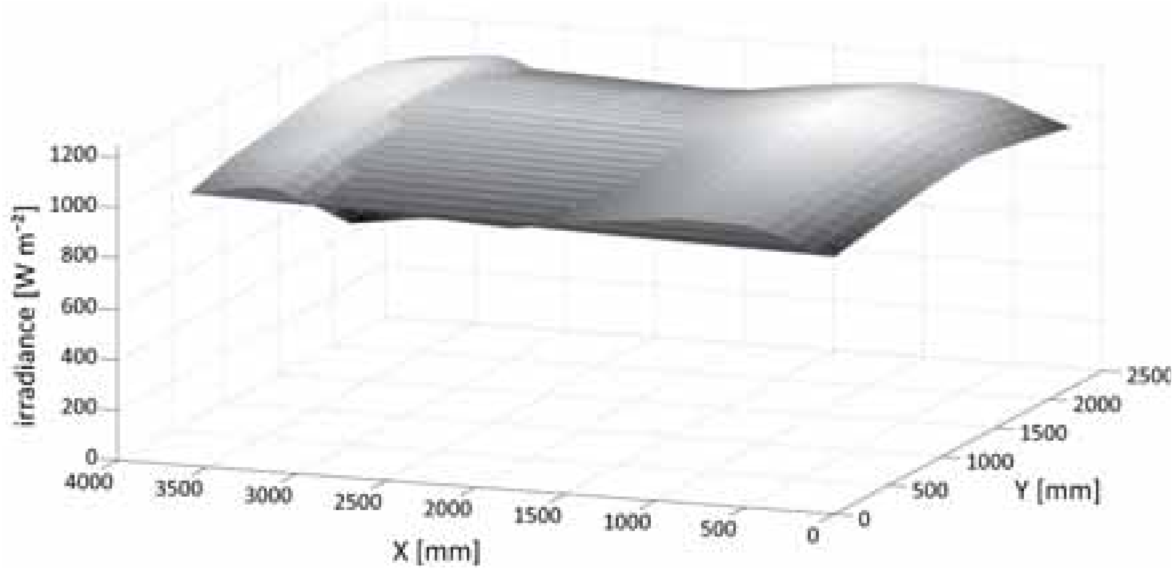

Fig. 6: Irradiance homogeneity measurement in the test area

The above described dynamic solar simulator is fulfilling all planned tasks. Its mechanical shading device is working unobstructed and enables together with the electric dimming solar irradiances between 100 and almost 1200 W m^{-2} in steps of approximately 50 W m^{-2}. The spectral distribution for all discrete selectable positions is within the interval of tolerance. The homogeneity of the irradiance is even better than the 15 % deviation allowed by EN 12975-2: 2006.

4. Adaptation of the outdoor test procedure of solar thermal systems according to ISO 9459-5 to indoor test conditions

If a system test is performed with the Dynamic System Test Method (DST) according to ISO 9459-5: 2007, the measured data are evaluated by using the InSitu Software ISS by Spirkl (1997). Using this method the characteristic system parameters are derived which can then be used for the long term performance prediction (LTP) to determine the solar fraction f_{sol} of the system. For the adaptation of the outdoor test procedure to an indoor test, it is necessary to define appropriate artificial radiation profiles. To do so, artificially generated “measured data”, so called “synthetic data” were used. These pseudo-measurements were generated by means of TRNSYS simulations and evaluated with the InSitu Software ISS (Spirkl, 1997) according to the procedure specified in ISO 9459-5: 2007.

In a first step a TRNSYS model of a forced circulation solar domestic hot water system was implemented into TRNSYS 16.1 to generate these data. This SDHW system has been tested according to the DST method under outdoor conditions before and is therefore suitable as a reference system. The system has a collector area of 4.7 m² and a store volume of 300 litres. The validation of this TRNSYS model required for the generation of the artificial measurement data was performed in the following way: Measured data (hemispherical and diffuse irradiance in collector plane, collector and storage ambient temperature, cold water inlet temperature and cold water (load) mass flow rate) recorded during the outdoor test sequences performed with the system were used as input data for the TRNSYS system model. By re-simulating the test sequences with the TRNSYS model output data such as e.g. the storage hot water outlet temperature were calculated. These “synthetic measurement data” were then used as input data for the ISS software to determine the characteristic system parameters that provide the basis for the annual system simulation.

The results of the annual system simulation can be characterized by the solar fraction f_{sol}. To validate the TRNSYS system model the solar fractions determined based on an evaluation of the measured data and the synthetic data can be compared. Fig. 7 shows the comparison for different daily draw off volumes. As can be seen from Fig. 7 the differences in the solar fractions Δf_{sol} is below one percentage point (absolute) for all draw off volumes, indicating a good agreement between the results gained from measured data and the ones determined on the basis of synthetic data. Based on these findings the TRNSYS system model can be considered as validated.

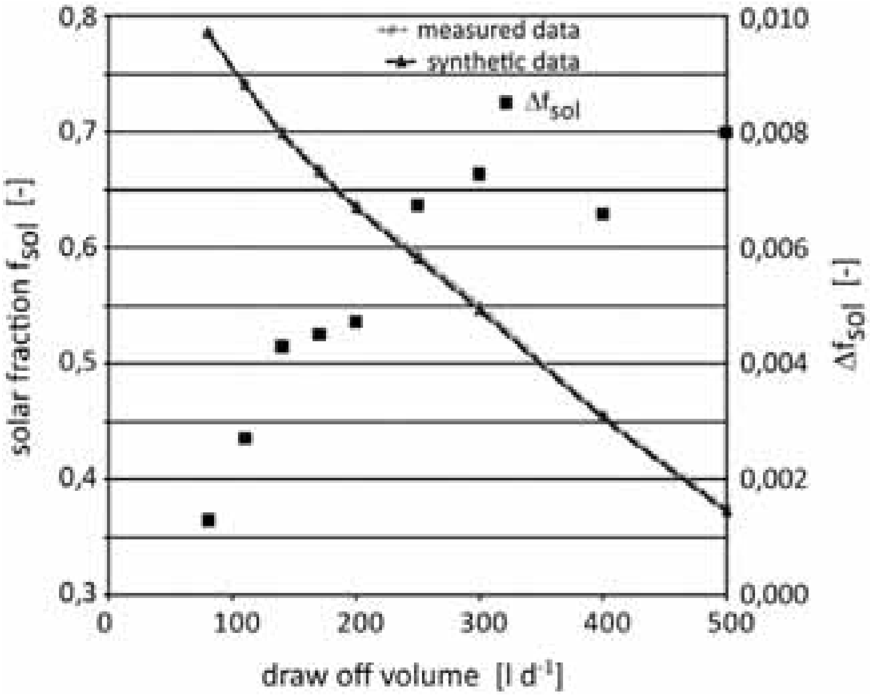

Fig. 7: Resulting solar fractions f_{sol} and deviation Δf_{sol} determined with ISS based on measured and synthetic data

In order to investigate the influence of different indoor test conditions on the system test results simulations were performed with different radiation profiles and ambient temperatures. Within the solar simulator, the radiation intensity can be varied as shown e.g. in Fig. 4. The incidence angle of the lamp array to the collector support rig is fixed, thus the ecliptic cannot be reproduced. The ISS software is taking the hemispherical irradiance over the whole day into account. Hence the irradiance on the collector G_{ISS} [W m^{-2}] has to be recalculated to be similar to outdoor measured radiation profiles. This is done using equation 1:

$$G_{ISS} = \frac{G_{b_{simulator}}}{IAM} + \frac{G_{d_{simulator}}}{K_{\theta d}} \qquad \text{(eq. 1)}$$

$G_{b_{simulator}}$ [W m^{-2}] is the beam irradiance during the measurement within the solar simulator, $G_{d_{simulator}}$ [W m^{-2}] is the diffuse irradiance, IAM [-] is the incident angle modifier and $K_{\theta d}$ [-] is the incident angle modifier of the diffuse solar irradiationThe IAM is calculated as a function of to the collector tilt angle, the day to be simulated and the location. For the following simulations a sequence of days representing irradiation conditions at the end of June at the location Würzburg was assembled. Using the mechanical shading device to produce low irradiances will lead to higher diffuse fractions compared with a not (or partially) shaded lamp array. As it is almost impossible to measure the diffuse fraction of the irradiance within the solar simulator, the diffuse irradiance was set, according to experience at ITW with an older solar simulator, to a constant value of 15 % of the hemispherical irradiance for all radiation levels (see Fig. 4) during all simulations.

4.1. Investigation of the influence of the ambient temperature

At first the influences of the collector ambient and store ambient temperature has been investigated. The radiation profile of the "day" used to determine the possible influences is shown in Fig. 8a. Plotted is the irradiance over time. The daily irradiation of this day is 20.83 MJ m^{-2}. To identify the effect of varying or constant store and collector ambient temperatures during the test sequences two simulations, each consisting of 10 similar days (see Fig. 8a), have been accomplished. The first simulation was done with a constant ambient temperature of 20°C for all test days. The solar fractions f_{sol} resulting from the LTP are depicted in Fig 8b as "const. temperature". Plotted is f_{sol} for different draw of volumes. The second simulation was done with a varying ambient temperature which is described by a sinus-function with a minimum at hour 5 of 12.5°C and a maximum at hour 17 of 22.5°C for all test days. Collector and store ambient temperature where equalized as the collector and store are within the same climate chamber. f_{sol} resulting from the LTP is depicted in Fig. 8b as "varying temperature". Furthermore the relative deviation between the two curves is shown as Δf_{sol}.

The maximum observed relative deviation occurs for draw-off volumes larger than 400 l but is still below 1 % absolute. Thus the system model used by ISS determines the model parameters characterizing the storage and collector heat losses correctly and independent of the ambient temperature during the test sequence. Therefore it can be stated that a varying or constant collector and storage ambient temperature does not have an identifiable influence on the solar fraction determined by the test method according to ISO 9495-5 (2007).

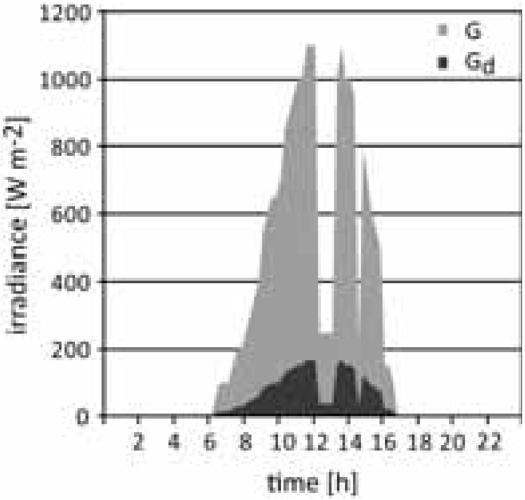

Fig. 8a: Hemispherical (G) and diffuse irradiance (G_d) during the "day" daily irradiation in collector plane: 20.83 MJ d^{-1} m^{-2}

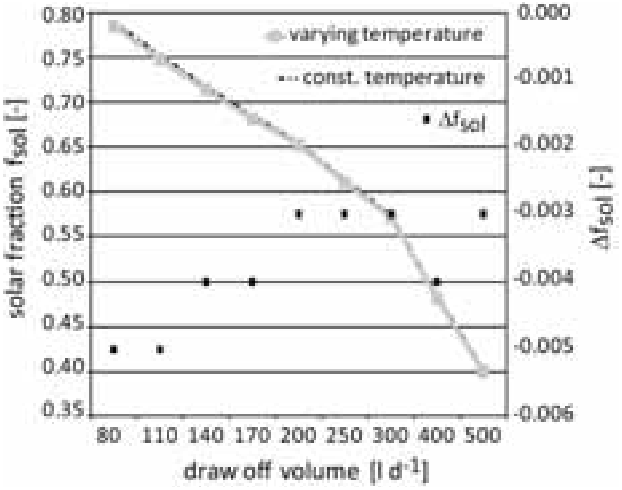

Fig. 8b: Results determined for constant and varying ambient temperature

4.2. Investigation of the influence of the radiation profiles

At second the influence of the radiation profiles on the results of the system test was examined. For this many different radiation profiles have been investigated in addition to the one shown in Fig. 8a. Profiles without a realistic natural shape, like rectangular profiles, lead to stronger deviations in the results, represented by the solar fractions, compared with the results determined by using the outdoor measured data. Therefore these profiles were not used for further contemplations. Profiles with a daily irradiation in the collector plane from 12 to 26 MJ m^{-2} have been created and used for the investigations as a minimum daily irradiation of 12 MJ m^{-2} is required by ISO 9459-5: 2007. Uniform sequences consisting of several identical days as well as sequences of mixed days were used. Fig. 9 shows an exemplary sequence of 6 days representing a possible so called "sol-sequence" (see ISO 9459-5: 2007 for further information), consisting of two different profiles arbitrarily mixed.

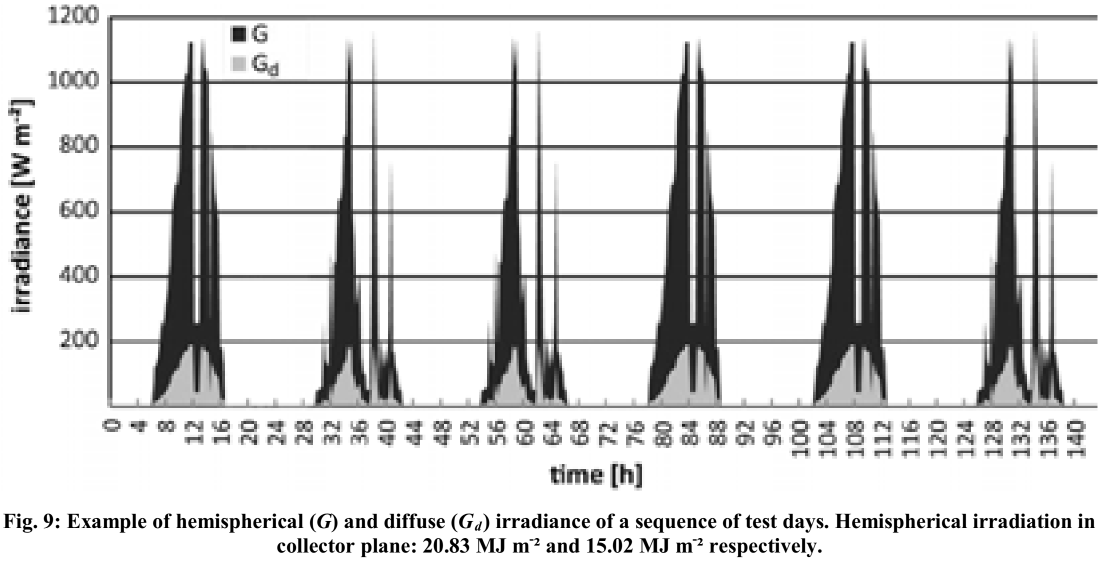

Fig. 9: Example of hemispherical (G) and diffuse (G_d) irradiance of a sequence of test days. Hemispherical irradiation in collector plane: 20.83 MJ m^{-2} and 15.02 MJ m^{-2} respectively.

In Fig. 10 the deviation of the determined solar fractions for several possible sequences related to the f_{sol} determined based on outdoor measurement are plotted versus the daily draw off volume. The bars above and below the zero-line indicate the ± 5 % relative error range of the outdoor measurement, indicating the deviation in f_{sol} in % absolute. The obtained maximum deviations for these sequences are lesser than the error range. If the sequence consisting of only the profile with a daily irradiation of 20.83 MJ m^{-2} d^{-1} is used (●), the obtained deviation is less than ± 2% relative for all draw off volumes, compared to the original results determined based on real outdoor measurement.

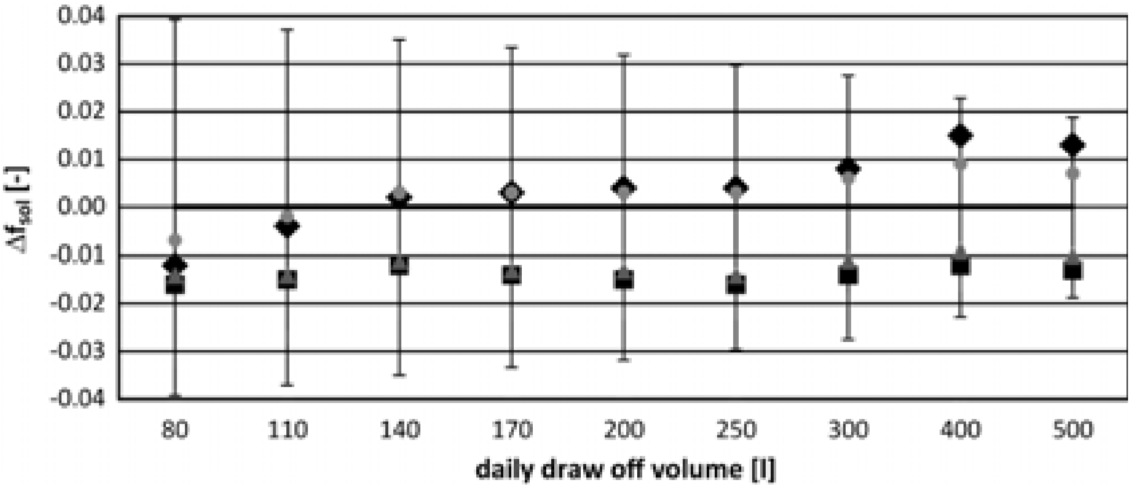

Fig. 10: Deviation of solar fractions Δf_{sol} determined for different radiation profiles sequences:
▲ sequence consisting of 2 different radiation profiles arbitrarily mixed with daily irradiation of 23.54 MJ m^{-2} d^{-1} and 12.94 MJ m^{-2} d^{-1}
♦ sequence consisting of 2 different radiation profiles arbitrarily mixed with daily irradiation of 20.83 MJ m^{-2} d^{-1} and 15.12 MJ m^{-2} d^{-1}
● sequence consisting of 1 radiation profile with daily irradiation of 20.83 MJ m^{-2} d^{-1}
■ sequence consisting of 1 radiation profile with daily irradiation of 15.12 MJ m^{-2} d^{-1}
I is the ± 5 % relative error range by Naron and Ree (1999)

5. Conclusion

A new solar simulator has been designed and constructed at ITW. Its main technical innovation is a computer controlled lamp array with a mechanical shading device. It allows varying irradiance levels from below 100 W m^{-2} to almost 1200 W m^{-2}. The test area has a size of approx. 10 m^2 and enables to test up to two collectors in parallel or one complete solar domestic hot water (SDHW) system. For the adaptation of the outdoor test procedure acc. to ISO 9459-5: 2007 to indoor tests, suitable operation conditions of the solar simulator have been determined. TRNSYS simulations for a SDHW system where performed to produce synthetic system output data for different radiation profiles. The results for four different sequences of radiation profiles have been shown. The deviations of the resulting solar fractions are within a range of ± 3.5% relative compared to the solar fraction determined based on outdoor measurement. Since this is below the typical inaccuracy of ± 5 % (Naron and Ree, 1999) of the DST method according to ISO 9495-5: 2007 the presented approach of performing indoor system tests is theoretically appropriate for performing standardised tests according to ISO 9495-5: 2007.

In the next steps, the presented simulations have to be validated by real measurements in the dynamic solar simulator. The resulting solar fractions determined of two different forced circulated systems and one thermosiphon system by measurements in the dynamic solar simulator will be compared to the results determined by outdoor measurements. Furthermore it is intended to perform investigations if it is possible to reduce the time for testing for instance by shortening the "night" period which can be easily done in the solar simulator. The possibility for performing standardized indoor system tests is a large step forward toward more flexible and accelerated system test procedures.

6. Acknowledgement

The investigations described in this paper where part of a project funded by the German BMU (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit / Federal Ministry for the Environment, Nature Conservation and Nuclear Safety) under the grant number 0325954A and managed by PtJ (Projektträger Jülich / Project Management Jülich). The authors gratefully acknowledge this support.

The sole responsibility for the content of this document lies with the authors.

7. Nomenclature

Symbol	Unit	Quantity
AM	-	Air mass
f_{sol}	-	Solar fraction
G_b	W m^{-2}	Beam irradiance
G_d	W m^{-2}	Diffuse irradiance
IAM	-	Incident angle modifier
ISS	-	Insitu Scientific Software (Spirkl, 1997)
$K_{\theta d}$	-	incident angle modifier of diffuse solar irradiation
LP	%	Lamp power
LTP	-	Long term performance prediction
MS	°	Mechanical shading
$SDHW$		Solar domestic hot water

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