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Status and first results of the DUKE project – Component qualification of new receivers and collectors

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Abstract

One option to improve the cost-effectiveness and environmental friendliness of parabolic trough power plants is the utilization of water/steam in the solar field, the so-called direct steam generation (DSG). First commercial stand-alone plants using DSG are now in operation in Thailand (parabolic trough with superheating by Solarlite) and in Spain (linear Fresnel for saturated steam by Novatec Solar). To further bring down the costs of a DSG solar field, the research project DUKE aims at the development and demonstration of a commercially applicable once-through mode design.

The demonstration will be done at the DISS test facility at the Plataforma Solar de Almería (PSA), Spain, by the DLR-Institute of Solar Research in close collaboration with the Spanish CIEMAT. For this purpose, the DISS test facility was upgraded to a length of 1000 m by three new collectors. It now has commercial-scale size and, in addition, is able to stand 500 °C and 110 bar at the outlet [1].

The construction and commissioning of the new plant has been completed (see Fig. 1) and the first test period has started in May 2013. The paper examines two aspects: illustrate the design changes of the solar field and show the performance of the two new main components: the DSG receivers as well as the new collectors.

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Keywords: direct steam generation, heat loss characteristics, optical efficiency, once-through concept, solar boiler

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1. Introduction

One option to improve the cost-effectiveness of line focus solar fields is to directly preheat, evaporate, and superheat water/steam in the receiver tubes, the so-called direct steam generation (DSG). DSG is now applied commercially by Novatec Solar with its 30 MW_{el} Puerto Errado 2 Fresnel plant commissioned in 2012 [2] and by Solarlite with its 5 MW_{el} parabolic trough plant TSE-1 in Thailand, commissioned in 2011, generating superheated steam [3].

The basis for these plants was the development started in the 1990s. After fundamental research regarding evaporation in horizontal pipes, see e.g. [4], the DISS (DIrect Solar Steam) project was started in 1996 [5]. In the first phase of the DISS project a test facility was designed and constructed at the Plataforma Solar de Almería (PSA) in Spain. This facility consisted of 500 m of LS-3 collectors and is still known as DISS test facility. In the second phase of the project, the test facility was used to investigate the basic operation modes of DSG, which are recirculation mode, once-through mode and injection mode [6]. Based on the experience from DISS [7], a pre-commercial DSG plant for recirculation mode was designed in the project INDITEP [8]. Furthermore, during that project two new Eurotrough collectors with a length of 100 m each were added at the inlet of the DISS test facility and equipped with prototype receivers. Further component tests have been performed in the projects DIVA [9] and Real-DISS, the latter ones at a demonstration collector in Carboneras, Spain, for steam parameters of 500 °C and 110 bar [10].

The experience from first commercial plants is very good and suggests very robust and stable operation of the plants in recirculation mode [3]. In consequence, research now aims at further optimization of operation and maintenance (O&M), thermal energy storage development [11-13] as well as further solar field cost reduction. To achieve the latter solar field cost decrease, especially the once-through concept looks most promising [1].

Therefore, the once-through concept will be analyzed in detail in the project DUKE (Durchlaufkonzept – Entwicklung und Erprobung; Development and demonstration of the once-through concept) by the DLR Institute of Solar Research in collaboration with CIEMAT-PSA. The project's goal is to develop and demonstrate the once-through mode in parabolic troughs under real solar conditions and at a commercial scale. For this purpose, the DISS test facility has been extended by 300 m of Solarlite SL4600+ collectors. The new plant is now completely installed and commissioned. The tests for analyzing the once-through concept in detail are now ongoing.

This paper explains the new layout and design of the facility. The receiver tubes for 500 °C and 120 bar are characterized by heat loss measurements. The preliminary optical efficiencies and the method to calculate them are presented.

Nomenclature

BOP	Balance of Plant
CIEMAT	Spanish Center for Energy, Environment and Technological Research
DISS	Direct Solar Steam
DLR	German Aerospace Center
DUKE	Durchlaufkonzept – Entwicklung und Erprobung (Once-through concept – Development and Demonstration)
DSG	Direct Steam Generation
IAM	Incidence angle modifier
O&M	Operation and Maintenance
PSA	Plataforma Solar de Almería
A_{nom}	Nominal collector aperture area (here: module length times gross aperture width) in m²
c_1, c_4	Coefficients for heat loss characteristic in (W/m)/°C and (W/m)/ $°C^4$, respectively
d_i	Inner diameter in m
L_{coll}	Length of collector in m

G_b	Beam solar irradiance in W/m²
h	Specific enthalpy in kJ/kg
i, j, k	Indices, mainly used as superscripts for time indication
$\dot{m}$	Mass flow rate in kg/s
q_{HL}	Receiver heat loss in W/m
$T_{abs,°C}$	Temperature of the absorber tube's outer surface in °C
θ_{inc}	Incidence angle in degrees
w	(Fluid) velocity in m/s
Δt_{sample}	Sampling time/interval in s
η_{end}	End loss correction factor (dimensionless)
$\eta_{opt,0}$	Optical peak efficiency (assuming $\theta_{inc} = 0°$) (dimensionless)
ρ_{mean}	Mean density of fluid in kg/m³
τ_{res}	Residence time of fluid in a certain collector section in s

2. New DISS facility

During the DUKE project the DISS facility has been extended to a gross length of now 1000 m. A scheme of the plant is shown in Fig. 1. Two new collectors (#0A, #0B) are located at the inlet and one collector (#12) is located at the outlet of the loop. This is due to the original layout of the plant and assures that the piping is as short as possible. Water enters from the feedwater pump in the Balance of Plant (BOP) to collector #0A. From there, it is further preheated, evaporated and finally superheated. Various injectors can be used to control the end of evaporation or the outlet temperature. Depending on the chosen control concept and the prevailing steam parameters, one or two of the injectors are active [1]. The superheated steam is then forwarded to a heat exchanger to preheat the feedwater and is then condensed by an air cooler unit.

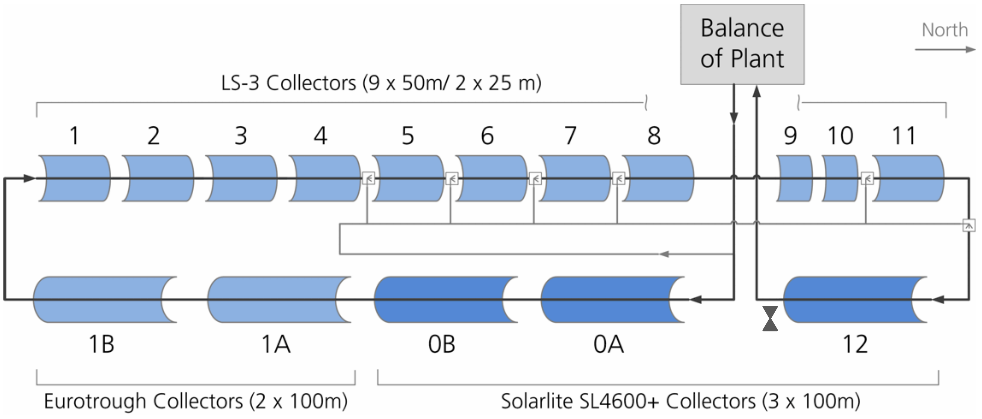

Fig. 1. Scheme of the new DISS test facility in once-through configuration.

The complete flexibility of the former plant has been maintained such that former tests could be repeated and the other operating modes could still be tested. Besides obvious piping and insulation works, the following improvements have been realized:

- Three new Solarlite SL4600+ collectors are installed with a length of 100 m each and an aperture width of 4.6 m, which results in an increase of total plant aperture area by more than 34 %.
- Inlet control valves were moved from the old inlet (before collector #1A) to the new inlet (before #0A).
- All receivers have been replaced by new SCHOTT PTR-70-DSG receivers for 500 °C and 120 bar.

- Collector #9, which had been used to analyze the influence of tilting on the flow pattern during evaporation, is now aligned horizontally.
- The collectors' loop is now divided into two design sections: from collector #0A to #7 designed for about 140 bar/ 400 °C and from collector #7 to #12 for 120 bar/ 510 °C.
- To meet the new design values, old piping has been replaced and new ATS ball joints have been installed in the section from collector #7 to #12.
- Two new high precision steam attemperators have been installed, one upstream and one downstream of collector #12.
- New injection instrumentation has been installed, e.g. injection volume flow meters to allow for better analysis of the energy balances and better process controllability.
- 57 thermocouples are installed every 4 m or 8 m in the zone of the end of evaporation to allow for a fast detection of fluctuations.
- At critical locations, adapted receivers with temperature measurements around a circumference within the vacuum are installed to check the temperature gradients within the cross section.

By means of these measures, the thermal power of the facility was increased by more than 40 %. At design conditions, the plant now provides more than 3 MW of thermal power. Fig. 2 provides an aerial view of the new facility.

Table 1 gives an overview of the collectors installed at the facility. Three collector types with different length are present. To calculate the nominal aperture area the module length of 12 m is taken as reference, such that a 100 m collector accounts with 96 m. The total aperture area of the facility is about 5196 m². The mean aperture width with respect to the total length and area is 5.41 m.

Fig. 2. Aerial view of the extended DISS test facility from south-west to north-east direction.

Table 1. Overview of collectors of the new DISS test facility.

Collector-name	Collector number	Collector type	Aperture width [m]	Length (Nom. module length) [m]	Nominal aperture area [m²]
0A	1	SL4600+	4.60	100 (96)	441.6
0B	2	SL4600+	4.60	100 (96)	441.6
1A	3	ET-100	5.76	100 (96)	553.0
1B	4	ET-100	5.76	100 (96)	553.0
1	5	LS-3	5.76	50 (48)	276.5
2	6	LS-3	5.76	50 (48)	276.5
3	7	LS-3	5.76	50 (48)	276.5
4	8	LS-3	5.76	50 (48)	276.5
5	9	LS-3	5.76	50 (48)	276.5
6	10	LS-3	5.76	50 (48)	276.5
7	11	LS-3	5.76	50 (48)	276.5
8	12	LS-3	5.76	50 (48)	276.5
9	13	LS-3	5.76	25 (24)	138.3
10	14	LS-3	5.76	25 (24)	138.3
11	15	LS-3	5.76	50 (48)	276.5
12	16	SL4600+	4.60	100 (96)	441.6
Total				**1000 (960)**	**5195.9**

3. Receiver characterization

New SCHOTT PTR-70-DSG receivers have been installed along the whole loop in order to be able to operate the collector field at steam parameters of up to 500 °C and 110 bar. For long term qualification, ten randomly chosen receiver tubes have been analyzed at the ThermoRec test bed of DLR in Cologne [14]. Those receivers have been installed at selected locations in the DISS collectors' loop and will be tested again at the ThermoRec at the end of the project to check if changes in the characteristics occurred. One reference receiver remains in the lab for comparison.

The results of the heat loss test show a very promising performance even at high temperatures. 50 K temperature steps have been applied from 300 °C to 500 °C. For some receivers, steps started at 100 °C and had an additional stationary point at 530 °C. The coating is stable up to 550 °C according to the manufacturer. The ambient temperature was almost the same during all experiments, varying between 20 °C and 21 °C.

Fig. 3 shows the 62 measurement points and the resulting heat loss characteristic. The length-specific heat loss characteristic found (unit W/m, assumed receiver length of 4.06 m) is described by the following regression with the absorber temperature in degree Celsius:

$$q_{\mathrm{HL}} = c_1 T_{\mathrm{abs,°C}} + c_4 T^4_{\mathrm{abs,°C}} = 0.16155 \frac{\mathrm{W/m}}{\mathrm{°C}} \cdot T_{\mathrm{abs,°C}} + 6.4407 \cdot 10^{-9} \frac{\mathrm{W/m}}{\mathrm{°C}^4} \cdot T^4_{\mathrm{abs,°C}} \qquad (1)$$

The standard deviation of this approximation is $\sigma = 9.1$ W/m. Fig. 3 shows the boundaries of the 95 % confidence interval, which is 2σ. This deviation only accounts for the experimental results, not for the uncertainties of the experiments themselves, which are mainly influenced by inhomogeneous temperature distributions along the absorber tube. The ambient temperature has a low influence on the tests and is not considered in the regression in accordance with [15]. Heat losses at low temperatures seem to be slightly overestimated by equation (1), but as uncertainties are much higher for these experiments and the temperature range is not that important for operation, this is acceptable.

Note, that for high temperature receivers, a characteristic with Kelvin temperature unit or with temperature only to the second power will lead to (partly significantly) higher standard deviations and should not be used. The quadratic fit, as formerly suggested e.g. in [16] for temperatures up to 400 °C, would even show systematic errors, underestimating the heat losses at high temperature and overestimating the losses at low temperature, see also [17]. Characteristics with temperature to the third power and more regression coefficients are closer to the results of equation (1).

The DISS test facility has been a test bed for various DSG receivers and, therefore, a single heat loss characteristic of the old receivers cannot be given. Fig. 3 shows instead a comparison with one former publication [18] as well as with the UVAC 3 receivers' heat loss data published in [19] and fitted with the same characteristics as in equation (1) by [17]. Even compared to the low UVAC 3 heat losses, the new receivers show more than 25 % less heat losses at 400 °C. It also outperforms the former DSG receivers from the component tests during the Real-DISS project in Carboneras, Spain [10]. A rough estimation from first experiments at the plant suggests that the heat losses are only about half the losses of the formerly installed DISS tubes.

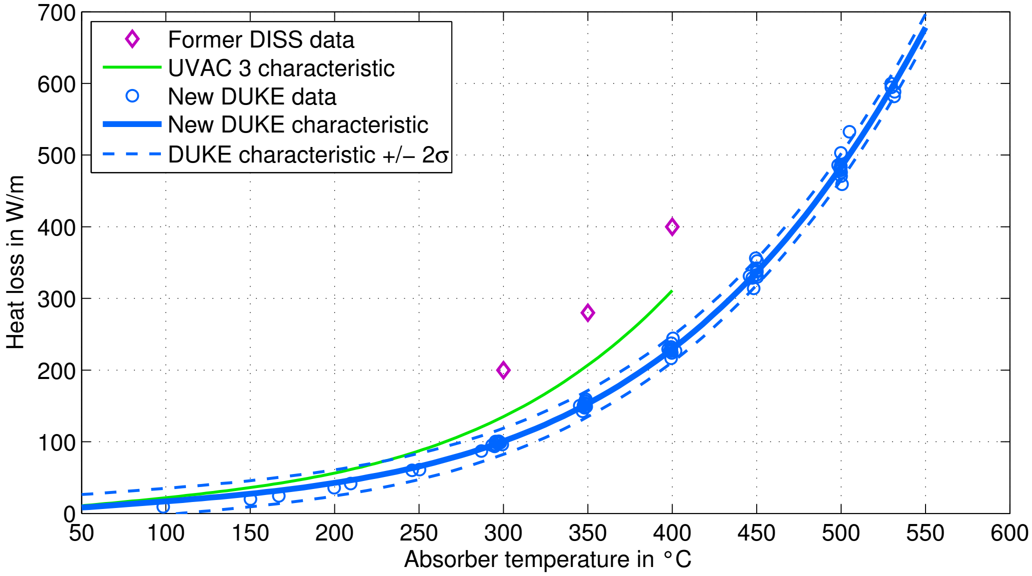

Fig. 3. Heat loss data and characteristics of the new DUKE PTR-70-DSG receivers as measured at ThermoRec by DLR, compared with heat loss of UVAC 3 based on [19] and former DISS data taken from [18].

4. Efficiency tests with subcooled water

4.1. Methodology

The three new collectors installed at the facility are prototypes using a torque tube together with glass fibre sandwich structures and thin glass mirrors connected to it by adhesive tape. Tests with cold, subcooled water have been performed to analyze their optical behavior together with the receivers. For simplicity, those tests are referred to as 'optical tests' in the following –although the authors are aware that it is a thermal efficiency test at rather low temperatures. At ambient fluid temperature, the influence of the heat losses is negligible and optical performance would be measured [20]. However, a certain temperature increase along the collector must always be present to measure the power input. In addition, the temperature of the tests performed for this analysis was in the range of 70 to 140 °C due to restrictions of the balance of plant. Nevertheless, heat losses are still very low at those temperatures and can be estimated by a receiver heat loss characteristic (see section above).

The incidence angle modifier (IAM) of the new collectors is not yet known, as prototypes are used and no ray-tracing analysis has been performed yet. Incidence angles at the times of the optical tests were in the range of 12 ° to 14 °. As a first estimate, a typical IAM curve of a Eurotrough type collector was chosen [21]. The IAM value varies between 0.9980 and 0.9994 during the experiments under the given incident angle. These variations are too small to distinguish between optical efficiency and IAM influences due to the dominant measurement uncertainties (see below). In consequence, an IAM characteristic must be derived in later stages of the test campaign. For estimating the optical efficiency, the IAM curve as above is used for this preliminary analysis. Additionally, the end losses of the receivers are included in the evaluation, while end gains do not occur in the DISS collector loop.

A pure stationary analysis of the data would require long, constant irradiation and fluid conditions which are barely realizable in a solar plant or collector loop. Therefore, a fluid volume approach is chosen to analyze the optical efficiency tests. This can be best explained as tracking of fluid volumes in the receivers. At first, the fluid volume velocity w is estimated by the inner diameter d_i, the current mass flow rate $\dot{m}$, and the mean density ρ_mean . With that, the residence time τ_res of the fluid volume to pass the whole collector length L_coll can be estimated:

$$\tau_\mathrm{res} = \frac{w}{L_\mathrm{coll}} = \frac{4\dot{m}}{\pi\, d_i\, \rho_\mathrm{mean}\, L_\mathrm{coll}} \tag{2}$$

The measurement data is taken in discrete time steps of
$j \cdot \Delta t_\mathrm{sample}$ with $j \in \mathbb{N}$. A fluid volume that enters the collector at measurement time index k will leave at about $k{+}i_\mathrm{res}$ with the rounded residence time index

$$i_\mathrm{res} = \left\lceil \frac{\tau_\mathrm{res}}{\Delta t_\mathrm{sample}} \right\rceil \tag{3}$$

During its residence in the collector, the fluid volume which enters the collector at time index k is exposed to the mean solar beam irradiance $\bar{G}_b^k$ as defined by

$$\overline{G}_\mathrm{b}^{\,k} = \frac{1}{i_{res}} \int_{j=k}^{j=k+i_{res}} DNI^j \cos(\theta_\mathrm{inc}^j)\, dj \tag{4}$$

The mean heat loss $\bar{q}_\mathrm{HL}^k$ is calculated accordingly assuming a linear increase along the collector. The enthalpy h is calculated from water/steam formulations depending on the measured temperature and pressure of time index k or $k{+}i_\mathrm{res}$, respectively. As we look for the optical peak efficiency $\eta_\mathrm{opt,0}^k$ we must also consider the end losses η_end^k and IAM^k of every measurement instant together with the corresponding DNI values. For discrete time systems the integral formulation of equation (4) can easily be reformulated to a summation. In consequence, the formula for the current optical peak efficiency determined from a fluid volume entering the collector at instant k results in

$$\eta_{opt,0}^k = \frac{\dot{m}^k \cdot (h_{out}^{k+i_{res}} - h_{in}^k) + \overline{q}_{HL}^{\,k} \cdot L_{coll}}{A_{nom} \dfrac{1}{i_{res}} \sum\limits_{j=k}^{k+i_{res}} \left(DNI^j \cos(\theta_{inc}^j)\, \eta_{end}(\theta_{inc}^j)\, IAM(\theta_{inc}^j) \right)} \tag{5}$$

A simple stationary approach would purely be based on values of the same time instant k without time shifting and summation/integration. A comparison of the stationary and the fluid volume approach is given in Fig. 4. The shifted temperature curve in the second diagram corresponds to the fluid volume method and indicates the outlet temperature that the fluid volume entering at time k would have at the outlet (the temperature is shifted backwards by i_res). The resulting efficiency varies by only about 0.2 %-points (77.34 % stationary, 77.11 % fluid volume approach, based on the nominal aperture area), because the experimental conditions were almost perfect with very low fluctuation in DNI and temperatures and especially during a long time. If tests were performed that only showed steady outlet temperatures for time intervals corresponding to the residence time of the fluid, the fluid volume method would still offer reasonable results, while the steady state approach would not provide constant evaluation conditions. This can be seen in the lower chart of Fig. 4. In the marked interval between 13.8 and 13.93 h, both approaches are nearly the same due to the rather constant conditions. However, with the fluid volume approach, the same results are already achievable starting from 13.72 h.

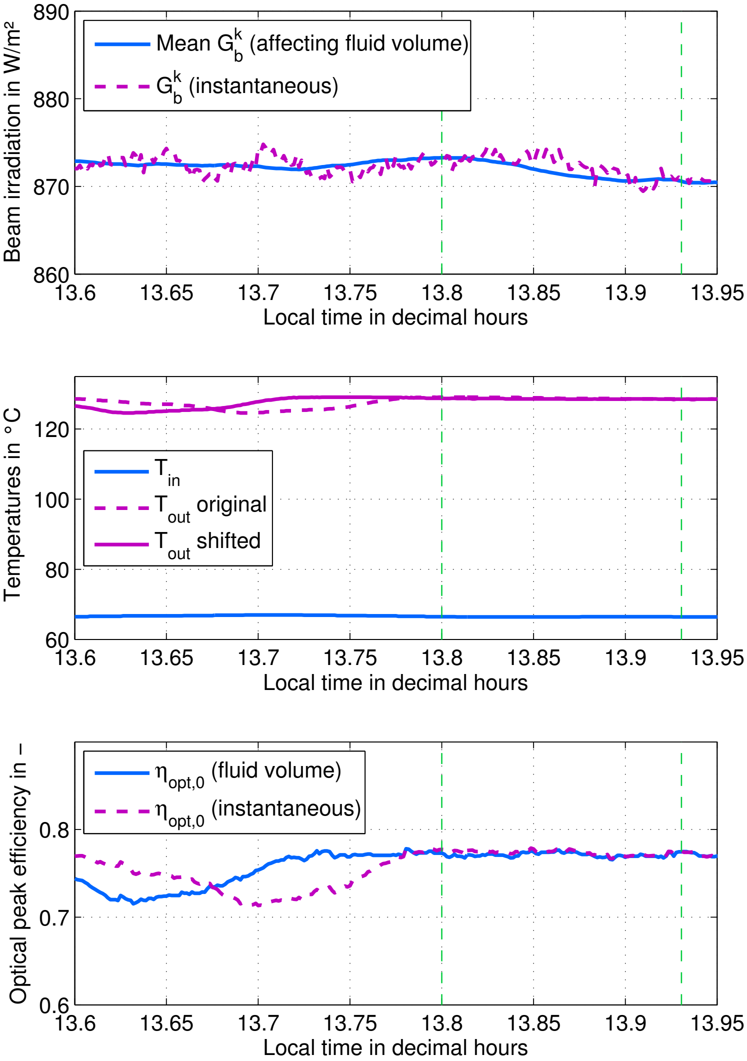

Fig. 4. Test of collector #12 with stationary and fluid volume approaches for experiment with steady state conditions.

Note, that this approach does not yet cope with increasing or decreasing inlet temperatures. Those result in a systematic underestimation (increasing fluid temperature; compare fluid volume approach in Fig. 4 between 13.65 and 13.7 h) or overestimation (decreasing fluid temperature) of the efficiency due to the heat capacity effects of the receivers' steel tube. If sufficient data is available, this could be done by a regression coefficient c_{eff} corresponding to an effective thermal capacity and including the current change of temperature by $c_{\mathrm{eff}} \cdot \partial T_{\mathrm{fluid}}/\partial t$, see e.g. [22]. Otherwise it must be considered in the uncertainties of the analysis, see e.g. [23].

Furthermore, the calculated peak efficiency corresponds to two additional limitations. One is the prevailing reflectivity of the mirrors (to be measured at the experiment) compared to the peak reflectivity (to be measured with absolute clean, washed mirrors). This ratio is usually referred to as cleanliness or cleanliness factor [20]. The second limitation is the extrapolation of the peak optical efficiency to higher temperatures. Due to the thermal expansion of the receiver, a performance drift could happen that must then be included in the models applying the peak efficiency.

4.2. Uncertainties

Table 2 provides an overview of the uncertainties of the experiments. An overall uncertainty will be calculated, if further experiments have been performed to reduce the type A uncertainties (number of different comparable experiments) according to the GUM [24]. In principle, there are only few possibilities to further reduce the uncertainties of type B. The measurement equipment is fixed, such that its uncertainties cannot be improved. The discrete time filtering uncertainty is supposed to be rather low and not contributing significantly to the overall uncertainty. Further confidence can only be gained by IAM determination and considering the dynamic effects of the tube walls' heat capacity. This will also be performed in the near future during the project.

Table 2. Overview of uncertainties during optical performance tests.

Effect	Uncertainty	Explication
Mass flow measurement	+/- 1.8 % of mass flow or +/- 0.045 kg/s	Specification of manufacturer
Temperature sensor measurement	+/- 1 K	Specification of manufacturer
DNI measurement	+/- 1.5 %	Estimation from [25, 26]
Pressure measurement	+/- 0.15 %	Specification of manufacturer
Discrete time filtering	Variation with about Δt_{sample}	Deviation by shift from continuous to discrete time; depending on stationarity; < 0.1 % in experiments
Heat capacity tube/system	To be determined	By estimating temperature change and according heat
Number of experiments	-	Only one or two experiments per collector; high uncertainty
Heat losses	About 0.5 % (depending on temperature)	Irradiated receivers, warm water do not fulfill ideal test conditions
IAM	About 1 % (depending on incidence angle)	No IAM known so far
Enthalpy calculation	+/- 0.1 %	Table from pressure/temperature to enthalpy

4.3. Results

The preliminary results of the first tests with subcooled water are summarized in Table 3. The optical efficiency is in the range of 77 %. However, the uncertainties are still high and further experiments should be done for a more reliable result. Furthermore, dynamic test evaluation will be used to decrease uncertainties in temperature changes; and IAM experiments will be performed during the year for a better characterization of the collector.

Table 3. Overview of preliminary optical performance of the new SL4600+ collectors as installed at DISS test facility.

Collector-name	Collector number	Nominal aperture area [m²]	Optical efficiency [%]
0A	1	441.6	77.3
0B	2	441.6	76.7
12	16	441.6	77.2

5. Summary and outlook

During the DUKE project the DISS test facility has been upgraded to provide more power and enable tests at high steam parameters of up to 500 °C and 110 bar. The facility has been equipped with three new collector prototypes of 100 m each and an aperture width of 4.6 m. Their efficiency was determined by a preliminary test evaluation and uncertainties were estimated. They showed a good optical efficiency in the range of 77 % based on the nominal (gross) aperture area of 441.6 m².

Furthermore, new SCHOTT PTR-70-DSG receivers are installed along the complete loop length of now 1000 m. Their heat loss characteristic was determined based on 10 randomly chosen receivers during laboratory tests at DLR's ThermoRec. The performance is very good with heat losses of 230 W/m at 400 °C and 485 W/m at 500 °C. The standard deviation of the results is 9.1 W/m.

The qualification of the new components is now used in stationary and dynamic simulation models of the plant. Based on these and on further dynamic experiments at the plant, the once-through concept will be analyzed in detail during the project as outlined in [1].

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