D11.6

Report on Measurement Uncertainty

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Executive Summary

The EU-funded research project - SFERA - aims to boost scientific collaboration among the leading European research institutions in solar concentrating systems, offering European research and industry access to the best research and test infrastructures and creating a virtual European laboratory. The project incorporates the following activities:

- Transnational Access: Researchers will have access to five state-of-the-art high-flux solar research facilities, unique in Europe and in the world. Access to these facilities will help strengthen the European Research Area by opening installations to European and partner countries' scientists, thereby enhancing cooperation.

- Networking: These include the organisation of training courses and schools' to create a common training framework, providing regularised, unified training of young researchers in the capabilities and operation of concentrating solar facilities. Communication activities will seek to both strengthen relationships within the consortium, creating a culture of cooperation, and to communication to society in general, academia and especially industry what SFERA is and what services are offered.

- The Joint Research Activities aim to improve the quality and service of the existing infrastructure, extend their services and jointly achieve a common level of high scientific quality.

This deliverable 11.6 is one results of the WP 11, Task 2 - Enhancement of measurement accuracy of heat capacity measurement bypass - within the Joint Research Activities.

During the SFERA-II project, the measurement accuracy of a facility called KONTAS-c_p consisting of a bypass with electric heating, temperature difference measurement and a Coriolis mass flow sensor to measure thermal heat capacity (c_p) of heat transfer fluid (HTF) is enhanced and an additional Coriolis mass flow sensor is included. The bypass is portable and can be coupled to practically any test facility using thermal oil. Such coupling enables the measurement of the heat capacity of the heat transfer fluid contained in the facility and also the calibration of installed mass flow sensors. Among others, mass flow and specific heat capacity are key measurands to carry out energy balance studies / efficiency measurements in thermal collector assessments.

The enhancement of the accuracy of heat capacity measurements is necessary because of insufficient data quality regarding the specific heat capacity of used thermal oils in parabolic trough applications, especially at elevated operation temperatures in the range of 200 to 400 °C. The objective of WP11 Task 2 is to reduce the in-situ measurement uncertainty of the specific heat capacity. The uncertainty in c_p was reduced to 1.0%.

The c_p-measurement bypass in combination with the inclusion of a highly accurate mass flow sensor (deliverable 11.7) lead to a high measurement accuracy of thermal performance tests of CSP components and systems. Thus, European research centres are enabled to offer a more reliable service to users from industry and research.

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1. Introduction

KONTAS-c_p is a DLR designed and built measurement bypass to precisely and accurately quantify the specific heat capacity of heat transfer fluids (HTFs) like Therminol VP1 and Sylterm 800 under CSP relevant operating conditions. That means temperatures in the range of 20 to 350 °C and pressure up to 18 bars. This calibration bypass is portable and can be coupled to practically any test facility using thermal oil by means of two flange connections. Relating to data acquisition, it is designed for stand-alone operation. Thus, it operates independently from any plant data acquisition system. The coupling of above described bypass enables the measurement of the heat capacity of heat transfer fluids contained in facilities and also the calibration of installed mass or volume flow sensors. Among others, mass flow and specific heat capacity are key measurands to carry out energy balance studies / efficiency measurements in thermal collector assessments.

WP11 Task 2A comprises the enhancement of the measurement accuracy of heat capacity measurements which happened against the background of insufficient data quality regarding specific heat capacity of thermal oils in parabolic trough applications, especially at elevated operation temperatures in the range of 200 to 400 °C. The high-precision and online heat capacity measurement of HTF at high temperatures is not state-of-the-art. Nevertheless, enhancing the measurement uncertainty seemed possible and also necessary for highly accurate performance testing of CSP plants (test facilities, demonstration and commercial plants). As a result of previous project activities and the commissioning of the measurement bypass, some potential improvements to reduce overall measurement uncertainty and optimize steady-state operation were identified beforehand. In continuation of these activities, individual influences (sensitivities) in the heat capacity measurement of all single measurands and recognized effects on the measurement have been cross checked. This detailed examination of all sensitivities, lead to a profound understanding of the measurement principle, its measurands and corrections. Whenever feasible and needed, adequate analytical or technical measures were applied leading to an enhancement of the measurement accuracy. Finally, the in-situ measurement uncertainty of the specific heat capacity was reduced to 1.0%.

This task is accompanied by WP11 Task 2B in which the bypass is equipped with an additional Coriolis mass flow sensor. Most test facilities have inline volume flow or even mass flow measuring devices to carry out energy balance studies. As a matter of fact, such sensors are integrated in piping and data acquisition system and thus cannot simply be taken out for calibration or functional checks. Over time, e.g. due to changes in temperature, an initially low measurement uncertainty of an integrated flow or mass flow sensor may change. By connecting the measurement bypass with a highly accurate mass flow sensor to facilities, an inline sensor can be calibrated and thereby the sensor specific and thus the overall measurement uncertainty can be decreased.

2. Measurement Setup

In this chapter, the measurement concept, the design of the c_p-measurement bypass and the setup for validation of its measurement accuracy is described.

2.1 Measurement Concept and Technical Design

The heat capacity is an intensive physical property that characterizes the amount of heat required to change a substance temperature by a given amount.

Equation 1:

$$\begin{aligned} Q &= H_2 - H_1 \\ &= m \times (h_2 - h_{1)} \\ &= m \times (h(T_{2,}p_2) - h(T_1 p_1)) \end{aligned}$$

with

$$p_2 = p_1 \qquad \text{(isobar)}$$

$$Q = m \times c_p \times (T_2 - T_1)$$

The specific heat capacity is the heat capacity per unit mass. Accordingly, the specific heat capacity at a constant pressure and steady mass flow can be calculated for a flow-through setup:

Equation 2:

$$\dot{Q} = \dot{m} \times c_p \times (T_{\text{out}} - T_{\text{in}})$$

$$c_p = \frac{\dot{Q}}{\dot{m} \times (T_{\text{out}} - T_{\text{in}})}$$

The general measuring principle for a flow through calorimeter is directly derived from this equation and leads to a basic measuring setup as shown in Figure 1. A mass flow (rate measured by flow meter) is heated by a heating device (heat flow rate measured) and the resulting temperature rise is measured continuously.

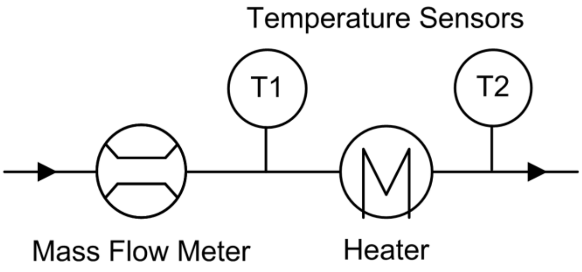

Figure 1: Basic setup, flow through (calorimeter) measurement of the specific heat capacity (c_p)

Accurate energy balance studies, based on the setup shown above, require steady state conditions regarding mass flow, inlet temperature, power supply and ambient conditions. The pursuit of stationary operation and minimal heat exchange with the environment complicates the general technical design and accounts for additional hardware devices described in [Hilgert 2012] surrounding the setup depicted in Figure 2.

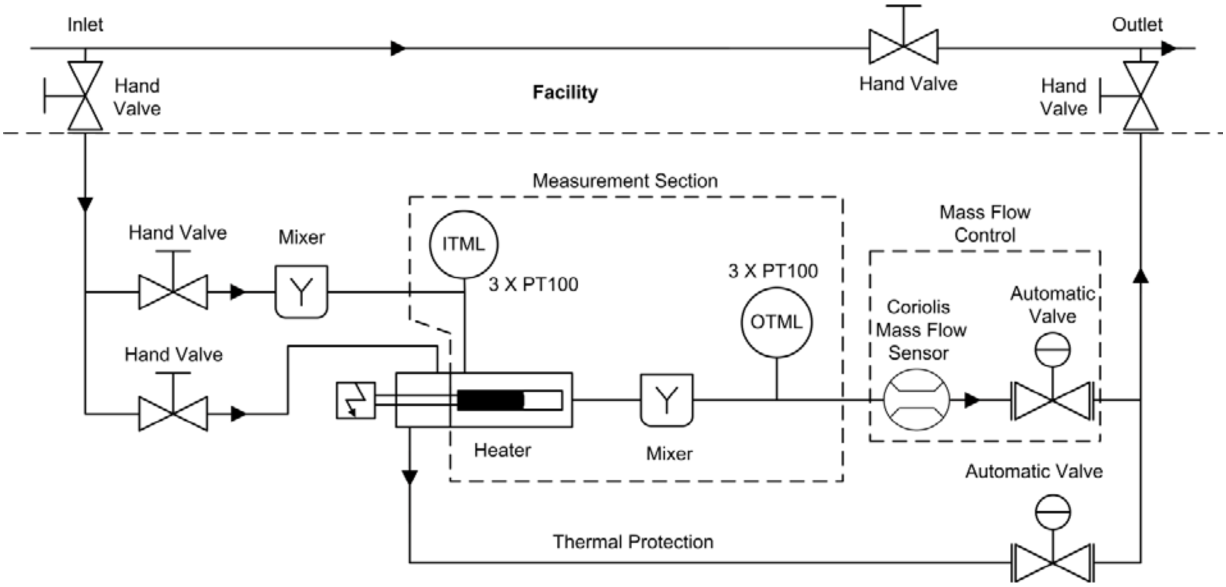

Figure 2: Technical layout for the c_p-measurement

The inlet temperature measurement location (ITML) and outlet temperature measurement location (OTML) define the energy balance volume boundaries or the so called measurement section (MS) of the bypass. To increase accuracy, volume and extend of the measurement section are minimized. The minimum required temperature difference across the MS at the design operation point depends on the measurement uncertainty of this temperature difference measurement. The uncertainty *u(delta T)* must be smaller than 1% to achieve the desired combined uncertainty $u(c_p)$ of c_p measurement. Taking into account the absolute uncertainty of the temperature difference measurement (0.2 K - see chapter 4.1) a minimal temperature difference of about 20 K over the measurement section is required. This value defines a specific mass flow rate and the necessary heat rate of the flow heater inside the energy balance volume in function of the specific heat capacity of the HTF. Measuring the heat capacity of water the mass flow is adjusted to 123g/s while the heater is operated at maximum power (~9500 W) due to an absolute uncertainty *u*(Power) of 20 Watt, see Table 1.

After the whole setup has reached steady state operation, meaning constant mass flow, delta *T* and inlet temperature, an operation point can be used for measurements. The minimum measurement time at each point depends on the time the fluid takes to travel through the MS, the so called residence time. In order to increase accuracy by averaging, a multiple of the residence time at each test point is evaluated. This factor was chosen to be always greater than five.

2.2 Validation Setup

All executed validation measurements (see Chapter 0) have been carried out using demineralized water at temperatures between 15 and 80 °C, because it is non-hazardous and its specific heat capacity is known with high accuracy. Comparing the combined measurement result to the heat capacity of water at particular mean temperatures enabled the identification of uncertainties and the influence of non-steady-state effects, e.g. fluctuations from ambient conditions. From a technical point of view, changing and optimizing an unpressurized system close to ambient temperatures containing water is much easier to handle than a pipe system with an oil-based HTF. The measurement device was hooked up to the water circuit shown in Figure 3. The validation setup was erected during commissioning and was reused during this and a previous validation measurement campaign.

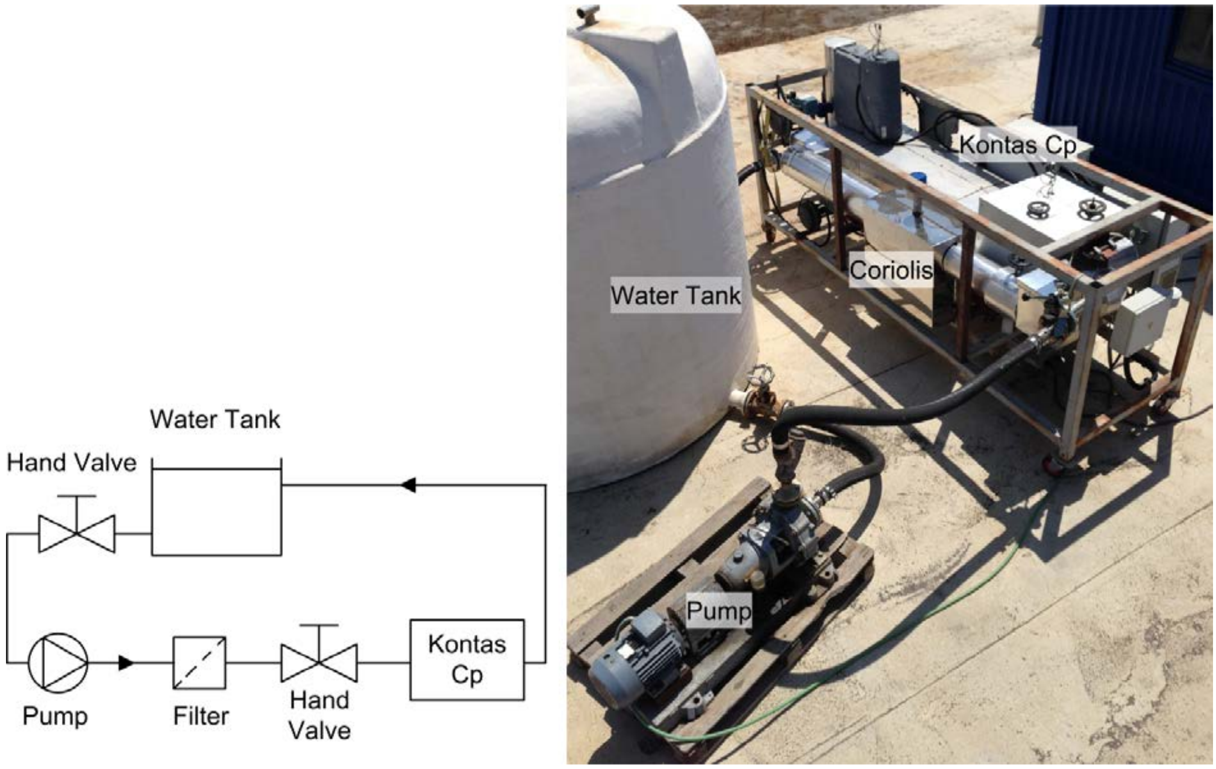

Figure 3 Validation water circuit

3. Measurement accuracy of the heat capacity measurement bypass KONTAS-c_p

The measurement bypass was designed, built and commissions in a former project. Enhancing the measurement uncertainty seemed possible and also necessary for highly accurate performance testing of CSP plants (test facilities, demonstration and commercial plants). As a result of this previous activity, some improvements to reduce overall measurement uncertainty and optimize steady-state operation were identified beforehand. These concepts and suggestion were taken as a basis for further developments during the course of WP11, Task 2 A of the SFERA II project.

3.1 Accuracy Requirement for c_p-measurement

The existing accuracy requirements on a heat capacity measurement can be derived from the general performance measurement situation in concentrating solar power applications, where one aims at measuring the thermal performance / useful heat of a thermal solar collector, collector loop or even a larger solar field section. The useful power of a parabolic trough unit is characterized by the enthalpy gain of the heat transfer fluid between its inlet und outlet.

Equation 3:

$$\begin{aligned}\dot{Q}_{use} &= \dot{H}_{out} - \dot{H}_{in} \\ &= \dot{m}_{out} \times h(T_{out}, p_{out}) - \dot{m}_{in} \times h(T_{in}, p_{in}) \\ &= \dot{m} \times c_p \times (T_{out} - T_{in})\end{aligned}$$

During performance testing of collectors, temperatures and mass flow are typically measured right at the facility, whereas the heat capacity value is taken from manufacturer data or from laboratory analysis. The enhancement of measurement accuracy of heat capacity measurements seemed necessary against the background of insufficient data quality regarding specific heat capacity of thermal oils in parabolic trough applications, especially at elevated operation temperatures in the range of 200 to 400 °C. The KONTAS-c_p measurement bypass is designed to be connected to a facility under investigation and measure especially at temperatures up to 350 °C[1]. Repetitive measurements at stepwise increased temperature levels serve to record the heat capacity of the HTF as a function of temperature. The desired uncertainty of c_p-measurement is 1. %. This requirement can be traced back to above mentioned performance measurement situation, where even small uncertainties may sum up to significant differences in annual yield. Thus there is a commercial interest in very accurate performance measurements and hence in accurate heat capacity measurement results.

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[1] The limitation in the maximum operation temperature of 350 °C results from a temperature limit of the utilized Coriolis mass flow sensor.

3.2 Detailed Analysis of Measurement Uncertainty

The heat capacity measurement is an indirect measurement. A measurement model (Equation 2) converts several quantity values into the corresponding value of the measurand (c_p-value). Such energy balance study, measuring an intensive physical property aiming at an overall / combined measurement uncertainty $u(c_p)$ of 1% requires a comprehensive understanding of the measurement principle, very accurate measurements of each single measurand as well as correction terms of potential influences affecting the measurement accuracy. This applies especially to the measurement bypass device because it is operated under fluctuating field conditions.

Uncertainties of type A (statistical) and of type B (manufacturer's specifications, experience etc.) are calculated and combined according to the “Guide to the Expression of Uncertainties in Measurement“ (GUM) for all measurands quantity values and also corrections. All recognized systematic deviations have been eliminated or corrected as described in Chapter 0. Sensor manufacturer data regarding measurement accuracy of the individual sensors and devices as well as the uncertainty estimation of corrections and measurement effects are used to calculate the propagation of uncertainties. To calculate the combined standard uncertainty of the specific heat measurement for uncorrelated quantities, the following equation is used.

Equation 4: $$u_c(Y) = \sqrt{\sum_{\mathrm{i}=1}^{N} \left(\frac{\partial f}{\partial x_\mathrm{i}} \right)^2 u^2\left(x_\mathrm{i}\right)}$$

The function f is given in Equation 2. Based on the data presented in Table 1 “Uncertainty, u(x)”, the combined two sigma uncertainty for design point operation is calculated. The sub-column headers indicate the source. “Manufacturer” refers to information given by individual sensor manufacturers. DLR entitles uncertainties recognized by research during measurement operation at the validation test rig presented in chapter 0.

Uncertainty in …	**Uncertainty, *u(x)***		**Sensitivity**
	Manufacturer	DLR	Design Point (demineralized water, 30 – 60 °C)
Uncertainty measurement devices			
Mass flow measurement (Coriolis mass flow sensor)	0.2 % of reading,	0.2 % of reading	7 %
Temperature difference measurement (PT100, 1/10 Class B)	0.03 K (0°C) to 0.12 K (100°C) absolute	0.2 K relative	76 %
Power measurement (Digital Watt meter)	0.2 % of max value (20 Watt)		3 %
Uncertainty in correction terms			
Heat loss of the MS correction (A)		10 W (static value) 100%	1.5 %
Heat loss electrical resistance correction (B)		10 %	0.01 %
Heater mean temperature shift correction (C)		10 %	0.01 %
Inlet temperature shift correction (D)		10 %	13 %
Resulting uncertainty in c_p			
Resulting uncertainty in specific heat capacity	**1.0** %		

Table 1: Uncertainties in measurands and corrections at design operating point (Demineralized water, ṁ = 123 g/s, T_{mean}=30…60°C, ΔT = 18 K, P_{el} = 9510 W)

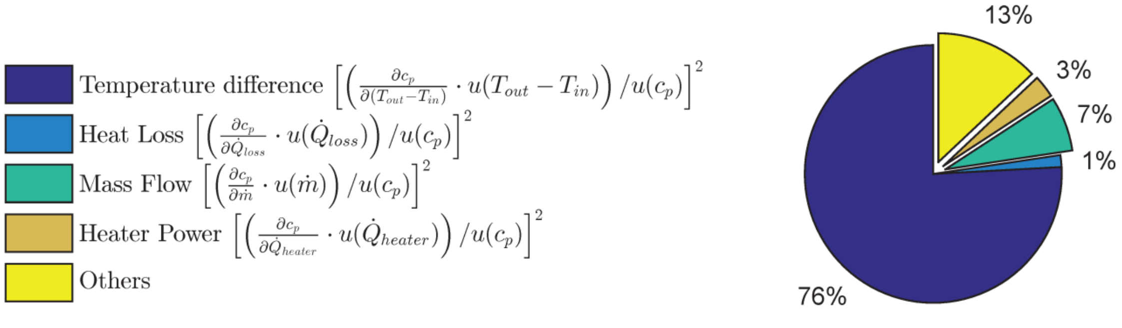

Figure 4: Sensitivities / uncertainty weighting at design operating point (Demineralized water, ṁ = 123 g/s, T_{mean}=30…60°C, ΔT = 18 K, P_{el} = 9510 W)

3.3 Systematic deviations and corresponding corrections

Correction terms are included in the measurement model as the conditions of measurement cannot exactly be maintained as stipulated in Equation 1. For instance, drifting inlet temperatures and heat exchange with the environment have to be considered. Such terms correspond to systematic deviations. As a correction term is either an estimate or a measurement model denoted with an uncertainty itself, there is a specific uncertainty associated with each correction listed in Table 1.

Static deviations that allow for linear compensation are corrected for during evaluation, individually at each metering point as defined in Chapter 0. Four applied corrections of systematic uncertainties are listed below. Attached uncertainties are given in Table 1.

A. Heat loss through the thermal insulation of the MS to the invironment
B. Heat loss due to electrical resistance of the conductor between heater and Watt meter
C. Steady change of the bypass mean temperature because of inlet temperature drift
D. Temperature difference correction as a function of residence time and a steady inlet temperature drift

A) Heat that leaves the MS through the thermal insulation does not contribute to the temperature rise of the HTF. This heat loss from the MS can be measured beforehand based on the knowledge (estimation) of the specific heat capacity of the used HTF. (See Chapter 4.4)

B) The heater cable and the inactive coil sections heat up because of electrical resistance. This power is not transferred to the fluid inside the MS. It is calculated and subtracted from the measured heater power.

C) Any steady drift of the inlet temperature provokes a temperature drift of the MS surrounding materials. The power to provoke this change in temperature of the surrounding material does not contribute to the temperature rise of the HTF. It is calculated and corrected for.

D) The mean inlet temperature is corrected by the product of slope of the temperature shift and the residence time. This means, the inlet temperature value is corrected to a value the inlet temperature had the residence time ago.

4. Enhancement of Individual Uncertainties

Accordingly to the uncertainty weighting (Figure 4) at design measurement conditions, individual influences (sensitivities) in the heat capacity measurement of all single measurands and recognized effects on the measurement have been cross checked. This happened to all uncertainty components including single measurands as well as corrections. The uncertainties were reduced by applying adequate analytical or technical measures to the software or hardware of the measurement device. In this regard, four different uncertainty fields have been established, investigated and reviewed: Temperature Difference Measurement, Power Measurement, Mass Flow Measurement and Heat Loss Measurement.

4.1 Temperature Difference Measurement

Three pairs of 3 mm casing tube Pt100 platinum resistance thermometer (PRT) are used to measure the temperature difference across the MS, see Figure 5.

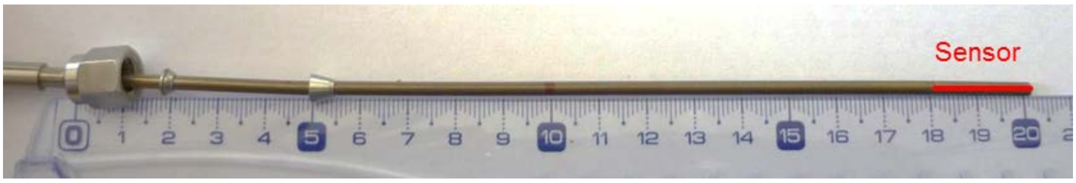

Figure 5: Single 3 mm casing tube Pt100 platinum resistance thermometer with cutting ring mounted, sensor indicated

For heat capacity measurements one PRT of each pair is located at the ITML and the other at the OTML. Each PRT pair connects to a two channel high accuracy data acquisition module assuming that, two analog input channels of the same hardware module have identical properties. In addition; pairing temperature sensors of the same kind and from the same batch, systematic uncertainties of the temperature difference measurement, as a result of data acquisition hardware and absolute sensor tolerances can be minimized.

In both temperature measurement locations sensor heads are wetted and thus have direct contact to the medium (Figure 6, left). The sealing to the environment is realized by cutting ring fittings allowing for quick sensor changes. On the inside of both measurement locations, little support tubes are mounted in order to prevent sensors from vibrating or unintentional contact to the tube wall or between two sensors. The immersion depth of the sensors has been set to 15 sensor diameters (3 mm) relative to the end of the support tube, accordingly to [Nicholas 2001]. Cutting ring fittings respectively PRT are arranged on a divided concentric perimeter as shown in Figure 6 right.

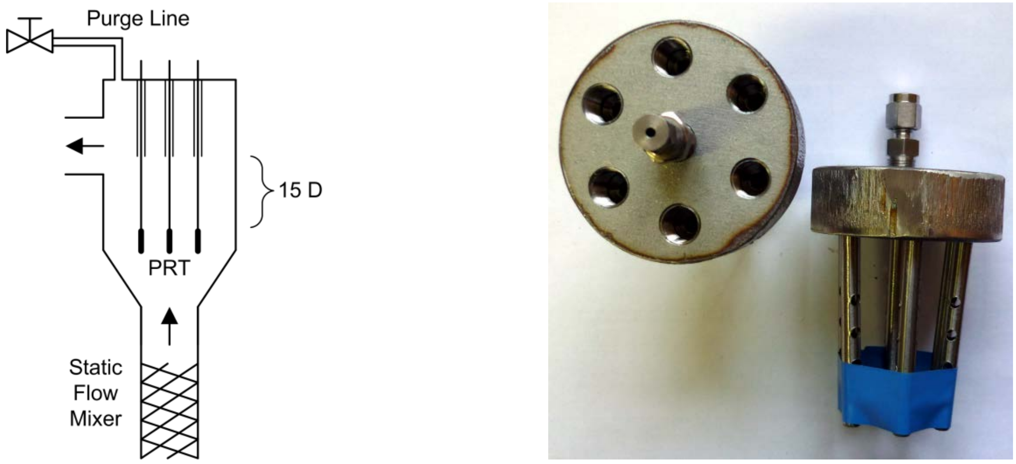

Figure 6: Temperature Measurement location, left: concept of OTML, right: blind flange with support tubes and one cutting ring fitting mounted to the purging whole, before welding

Deformations and vibration may have an influence in the sensor structure and thus in the sensor reading [DKD 2003] thus bending or the initial mounting of the cutting ring are only accepted before calibration. Any later deformation provokes the necessity of recalibration.

Accumulation of Gases at TML

Furthermore the existence or accumulation of gas bubbles in the measurement location can affect the reading of the sensors and must be eliminated. Figure 7 presents two different measurements with identical hardware in each case comparing the readings of six PRTs. One can see larger deviations between individual PRT readings when there is gas accumulated at the TML (Temperature Measurement Location). For this reason both TMLs can be purged to a lower pressure level down flow of the MS, not exposing any HTF to the environment.

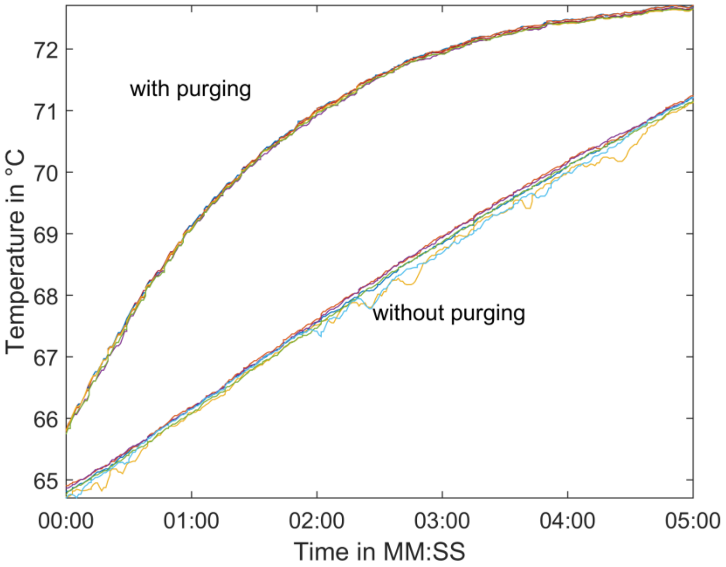

Figure 7: Gas bubbles accumulated at temperature measurement location affecting sensor reading, data from two different measurements (different slopes)

Thermal Convection at ITML

The inlet temperature location was designed to be as close to the heater as possible in order to limit the dimensions of the measurement section and thereby heat exchange with the environment. Having a close look to the details design of the inlet tube and the heater underneath, due to density differences hot HTF can possibly rise up from the heater and affect the temperature measurement at the ITML, causing a systematic deviation of the temperature difference measurement and thus uncertainties. Such potential backflow was countered by integrating an orifice between ITML and heater. The orifice makes for a local increase in flow velocity and thus prevents thermal convective backflow (Figure 8).

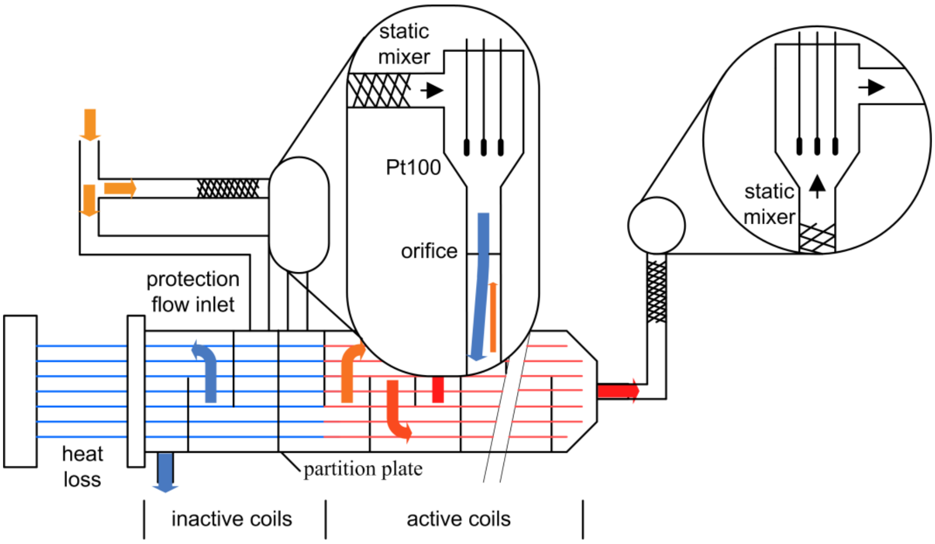

Figure 8: Location of orifice, prevention of backflow from the heater to the ITML

Relative Calibration

Frequent relative calibration measurements in the desired temperature range of the specific heat capacity measurement are essential for reliable uncertainty estimations. The comparison of all six sensors under uniform physical conditions uncovers deviations between all six sensors, which can be approximated and corrected applying calibration functions. To carry out such measurements, all six sensors are mounted to the outlet measurement location. In this position all sensor heads are located shortly behind a well-designed static mixer which connects the OTML to the flow heater. The static mixer is optimized for laminar flow and thus it is vertical oriented. Furthermore it is designed (type AGENS® AMX, AGENS Stratmann GmbH) to guarantee temperature homogeneity at the mixer outlet < 0.08 K, assuming a worst case scenario of a 20 K temperature distribution across the one inch tube diameter at the mixer inlet. Comparing the reading of the six sensors at six different positions within the same cross section also reveals above made assumption of uniform physical conditions for calibration to be applicable. See Figure 9 (right).

Uncertainty Estimation of Temperature Difference Measurements

The uncertainty of the temperature difference measurement was evaluated after a precise calibration and correction, respecting the following conditions:

A. Mass flow, electrical power and temperature range must fulfill the design measurement conditions. These change with different HTFs.
B. Significant plastic deformation or vibration of any of the sensors can be ecxluded
C. Accumulated of gases at TML is excluded by purging shortly before the measurement

Figure 9 (left) shows two close-ups with raw data of the same calibration measurement at two different temperatures. Both plots on the right show corrected data of a repeated measurement at the same temperature in each case.

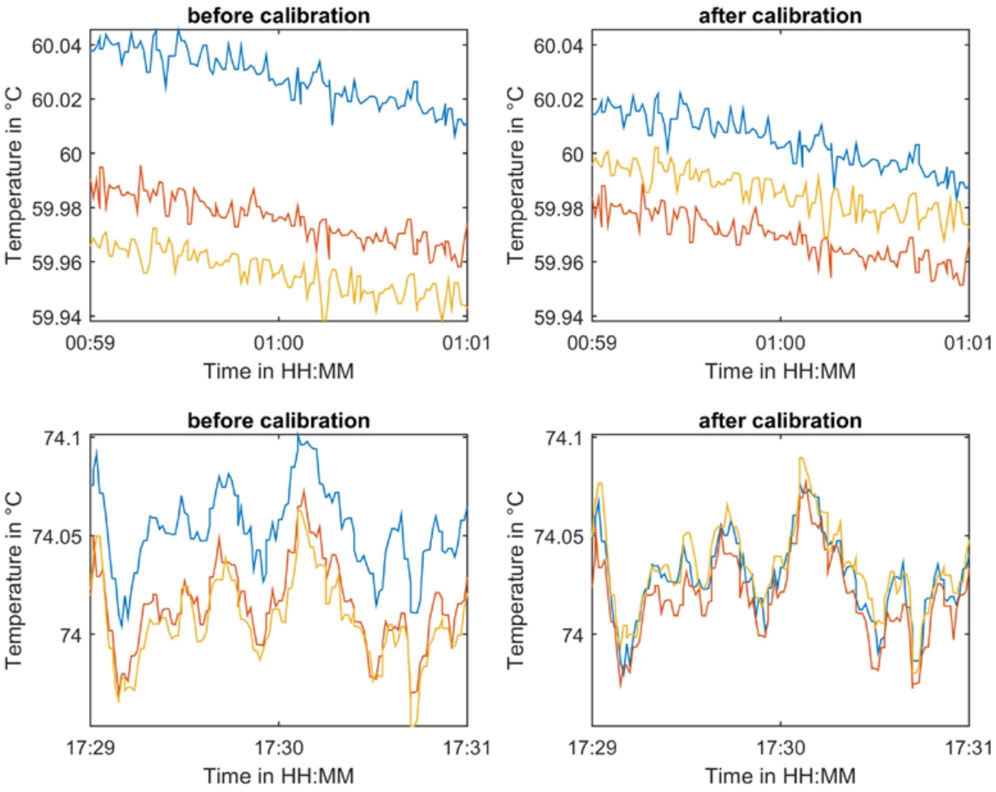

Figure 9: Three temperature readings at 60 °C and at 74 °C of the same calibration measurement left: raw data during calibration, right: repeated measurement applying the obtained correction functions

One can see that the difference between sensor readings at the OTML at any time is smaller than 0.1 K. Mounting three sensors to the ITML and comparing their readings reveals that deviations are always smaller than 0.1 K as well.

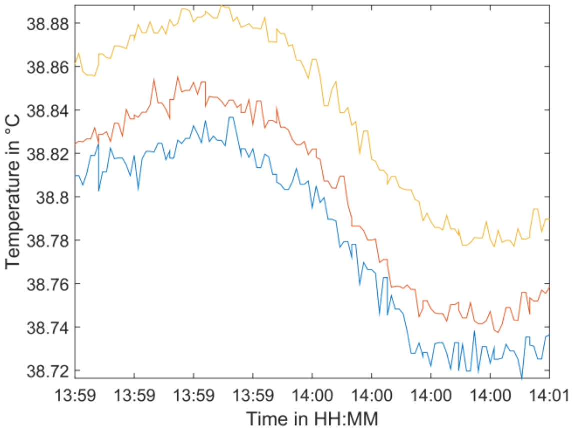

Figure 10: Three temperature readings at the ITML applying the obtained correction functions

Combining the reviewed uncertainties of the relative temperature measurement at ITML and OTML of 0.1 K each, results in an uncertainty of 0.2 K for the temperature difference. This is a conservative estimate which is assigned to the temperature difference measurement stated in Table 1.

4.2 Mass Flow Measurement

Accurate energy balance studies, based on the setup explained in chapter 2, require steady state conditions. For this reason a mass flow regulation has been integrated making use of the Coriolis mass flow sensor reading fed to a PID controller manipulating an automatic valve which regulates the mass flow through the measurements section. This mass flow regulation maintains the flow with a single standard deviation of 0.00014 kg/s (0.11% of reading) to the desired set value, see Figure 11.

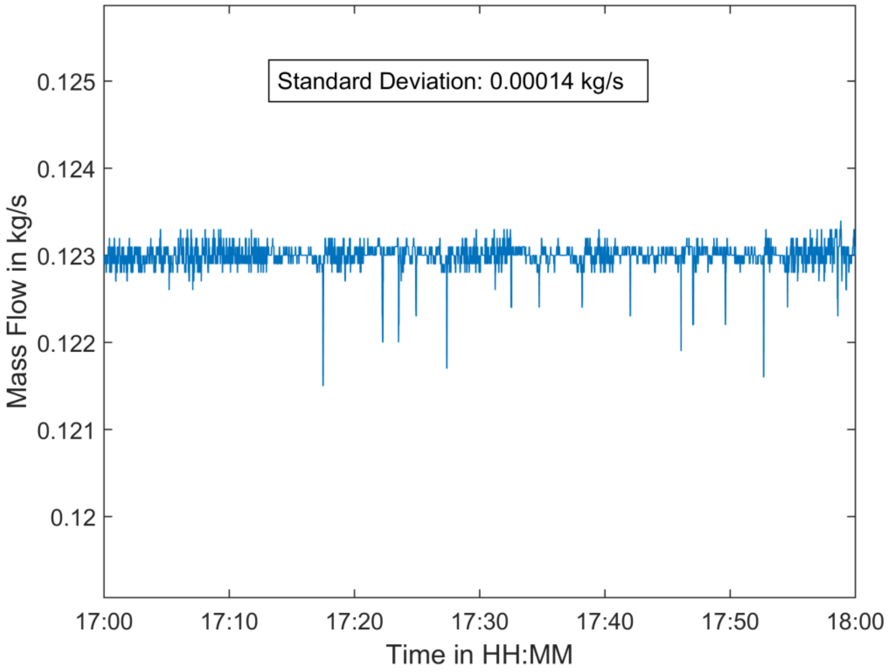

Figure 11: Typical mass flow reading during one hour of operation set point of mass flow regulation 0.123 kg/s

Above described regulation is needed during validation as well as during measurements using oil based HTF because the mass flow rate through the measurement bypass varies over time as the inlet pressure is most likely to changes with secondary system influences. In the case of the validation setup, the delivery rate of the pump was influenced by grid instabilities. In addition to the above described mass flow regulation, during validation measurements, the pump has been connected to an uninterrupted power supply (UPS) to compensate grid fluctuations.

The precision of the Coriolis sensor itself was checked by comparing its digital totalisator to the reading of a scale, metering the accumulated sensor throughput collected in a container. Beforehand the crane weigher was calibrated using a 50kg class M2 (± 8 g) precision weight, whereby it´s linearity (<0.2% over 50 kg) and absolute uncertainty (0.1 kg, <0.2% of reading) was proved.

Figure 12: left: calibration of the crane weigher using a 50kg class M2 (± 8 g) weight (loop tared)
right: measurement setup, empty barrel (tared) at the crane weigher

Diminishing the statistical uncertainty the revision measurement procedure has been repeated several times. The comparison of the Coriolis mass flow reading and the weighed accumulated throughput showed a deviation of the Coriolis of -1.1% to -1.8%. Using flying start/stop the uncertainty of the time interval, accumulating the mass flow was assumed to be one second. Accordingly the estimated overall uncertainty of the revision measurement procedure is 0.4% of the calculated result, which corresponds to an absolute deviation of 0.2527g/s at a flow-rate of about 125 g/s.

Figure 13: left: setup during measurement
right: linearity check, calibration weight on top of filled barrel

Subsequent the Coriolis mass flow sensor was sent to a certified calibration facility, SP Technical Research Institute of Sweden, to be precisely recalibrated. As an outcome of this calibration the error of indication of the Coriolis mass flow sensor was identified to be:

- -1,38% at 0,125 kg/s and 20°C
- -1,12% at 0,126 kg/s and 90°C.

Both calibration measurements were executed after mounting the thermal insulation of the device and performing a zero point adjustment.

Independently the temperature dependency of the Coriolis mass flow sensor transducer was investigated and decided to be kept in an air-conditioned electrical cabinet.

4.3 Power Measurement

The electrical power measurement, power transfer to the heater and conversion to heat was cross checked as described subsequently. The manufacturer specifies an uncertainty of the power meter of ±20 W in the range of 0 to 10 kW, see also Table 1. This uncertainty was reviewed by comparing the reading of this digital power meter (Yokogawa WT 230) to a recently calibrated and more precise power meter from a different manufacturer (LMG 450 by ZES ZIMMER Electronic Systems GmbH; uncertainty of ± 6.6 W absolute at 9500 W reading). For this kind of measurement both devices have been connected in series between power source and heater. During multiple comparison measurements the order of these two power meters and the cable connections have been changed in order to identify potential systematic uncertainties. The difference in reading of the Yokogawa WT 230 power meter and the ZES LMG 450 was found to be always smaller than 14 Watt. The combined uncertainty of this comparison can be quoted by adding u(Wt230) and u(LMG 450) resulting in ± 26.6 Watt. No significant contradiction to the manufacturer denoted uncertainty was found to be evident, thus the cross-check was successful. For this reason, the uncertainty specified by the manufacturer Yokogawa has been taken for the uncertainty propagation.

Figure 14 and Figure 15 show the power reading of both power meters connected in line for two different experiments. During the experiment of Figure 14, the ZES LMG 450 was directly connected to the power source and its outlet was connected to the Yokogawa power meter. The cable connections between both power meters and with the heater were as short as possible and of sufficient wire cross section. In Figure 15, the order of the power meters was interchanged. The difference between both power readings is always within the uncertainty of ± 26.6 Watt.

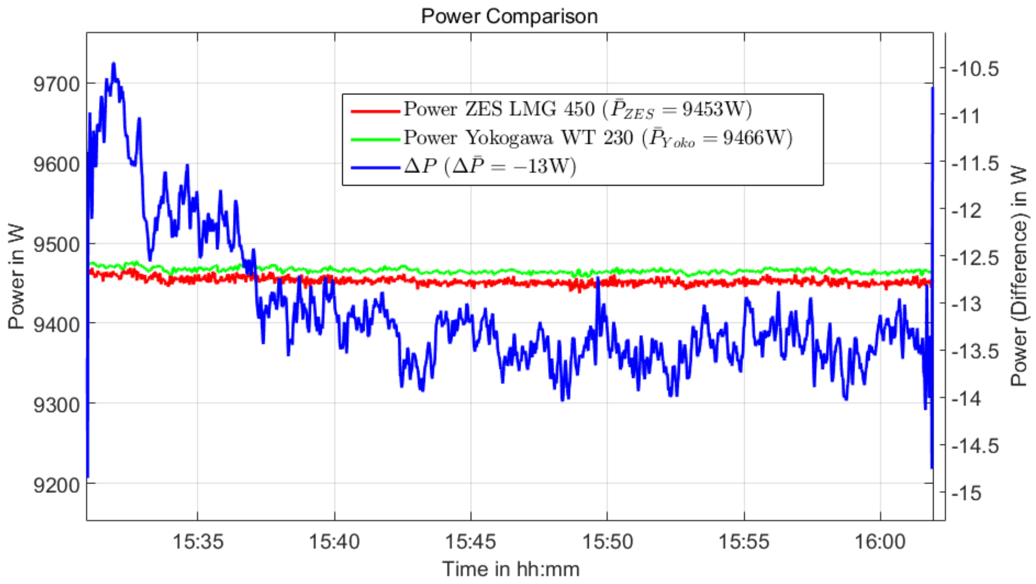

Figure 14: Power comparison measurement,
Connection order: Power source - Yokogawa WT 230 - ZES LMG 450 - heater

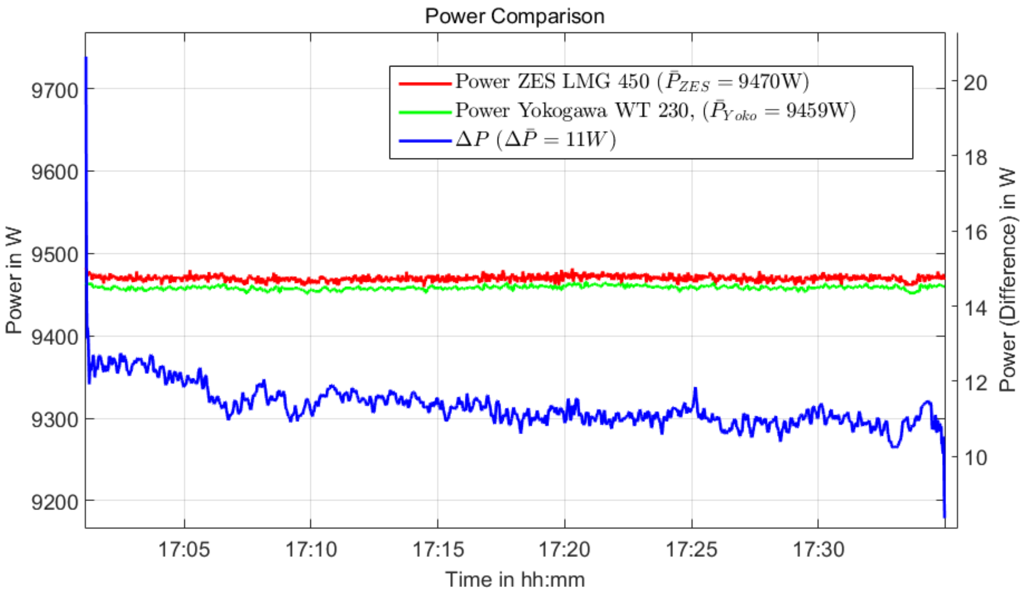

Figure 15: Power comparison measurement,
Connection order: Power source - ZES LMG 450 - Yokogawa WT 230-heater

Furthermore, the dimension of the active heating coils has been checked applying infrared thermography, as shown in Figure 16. By this measure, both active and inactive sections of the heating coils can clearly be distinguished. This measure aimed at verifying the design specifications of the heater coils, making sure that active heating coil sections are located within the measurement section boundaries. No hot heater coil was found to protrude the measurement section.

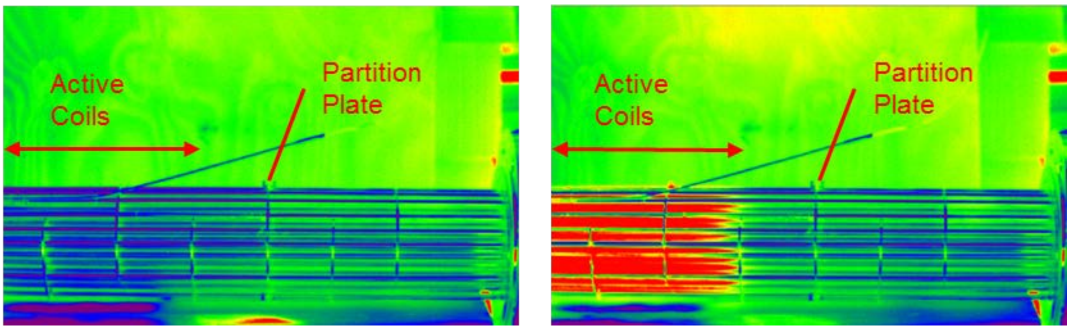

Figure 16: Exposed heater coils, IR image left: heater coils at ambient temperature right: heater in operation

4.4 Heat Losses

The term “heat losses” denominates heat flows to the environment that unintentionally or inevitably affect the MS or the electrical connection between heater and power meter.
The term heat loss is represented in Equation 5 and it combines the following phenomenon:

1. Heat loss from the MS to the environment through its thermal insulation
2. Heat loss due to a convective leakage of the MS
   (heated HTF leaves the MS via partition plate)
3. Heat loss from electrical conductor between power meter and heater
4. Heat loss due to a temperature drift (change) of the whole bypass facility

Equation 5: $$\dot{Q}_{\mathrm{HL}} = \dot{Q}_{\mathrm{HL\_MS}} + \dot{Q}_{\mathrm{HL\_conv.}} + \dot{Q}_{\mathrm{HL\_el}} + \dot{Q}_{\mathrm{HL\_DRIFT}}$$

Heat loss to the environment

In order to qualify potential heat losses of the MS to the environment, the bypass is operated under steady state conditions without electrical heating. The temperature difference between inlet and outlet temperature sensors as well as the mass flow rate is measured. A heat flow either entering or leaving the MS can be measured applying Equation 2 inserting the heat capacity of the particular HTF. A potential inlet temperature shift is corrected using correction D (see Table 1). During validation measurements heat capacity of water according to [IAPWS 1997] has been used leading to Equation 5:

Equation 6: $$\dot{Q}_{\mathrm{HL\_MS}} = \dot{m} \times c_{\mathrm{p,Water}} \times (T_{\mathrm{out}} - T_{\mathrm{in}})$$

A temperature difference of about 10 – 30 K to the environment was not exceeded because of a non-insulated water tank, thus maximum water mean temperature was limited about 60 °C. As a consequence of such small temperature difference to the environment the heat loss $\dot{Q}_{HL\_MS}$ was small and within the range of the measurement uncertainty of the temperature difference measurement. Figure 17 shows a typical graph measuring heat losses after the tank has been heated up to 62 °C during a heat capacity measurement beforehand. Ambient temperatures are between 35 and 25 °C.

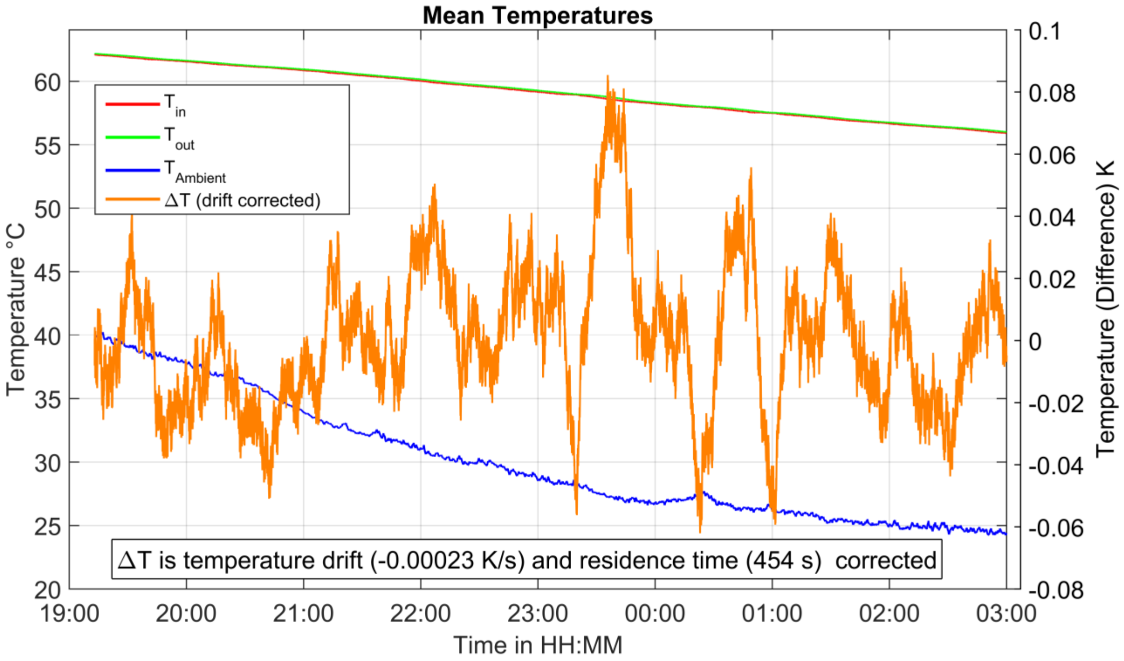

Figure 17: Temperature difference due to heat loss of the MS to the environment

As a consequence of several heat loss measurements similar to the one presented in Figure 17 and proved by the fact that temperatures inside the MS were always higher than ambient temperatures the temperature dependent heat loss to the environment at such low gradients was stipulated to be greater than zero. The heat loss was determined to be about 10 Watt and denoted with an estimated uncertainty of 100 %, see Table 1.

Heat loss due to a convective leakage of the MS

Mass flow (back flow) leaving the measurement section passing the partition plate after being heated, represents a violation of the determined control volume / measurement section. Thus, it must be guaranteed that during measurement operation no fluid is pushed out of the MS passing the partition plate. As the partition plate must have an annular clearance for thermal expansion and mounting reasons, leakage cannot be prevented totally. Diminishing the uncertainty of potential back flows additional circumferential barriers have been integrated. In addition, all annular gaps between heater tubes and partition plate have been shut applying silver solder, see Figure 18. During operation, the pressure outside the MS next to the partition plate is always higher slightly (0.1-1 mbar) than inside the MS. This way, no heated fluid can leave the control volume without passing through the OTML.

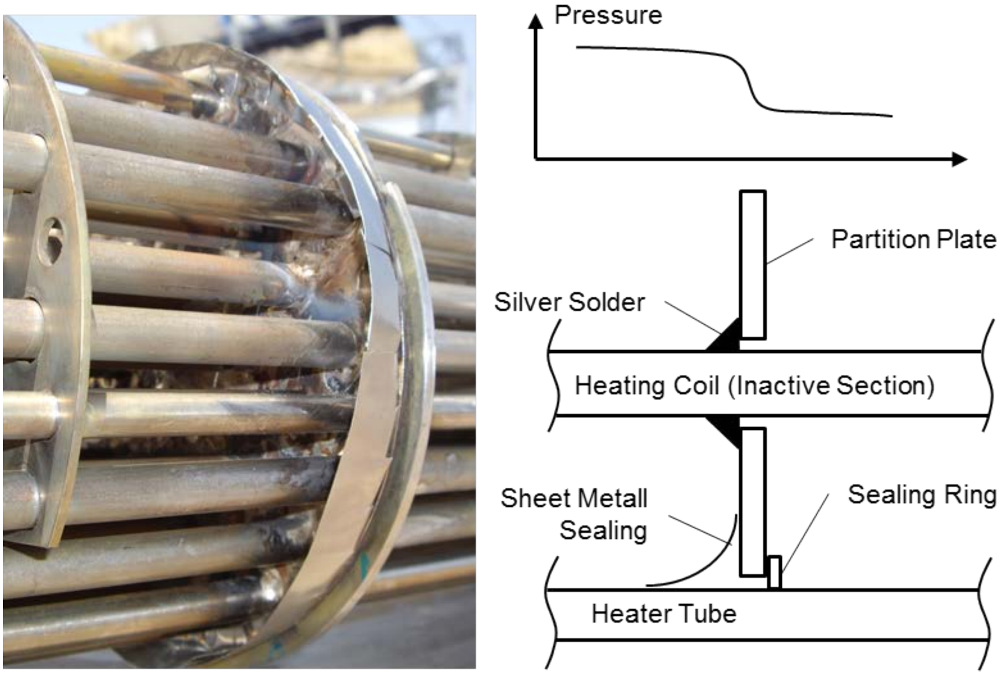

Figure 18: Partition plate with sealing, left: photo, right: sketch cross section close up

Heat loss from electrical conductor between power meter and heater

Both ohmic losses from the inactive parts of the heating coils and ohmic losses from the three phase cable are calculated and corrected during measurement evaluation accordingly to correction B, see Table 1. The heat loss of the three phase connection cable and the conductor inside the heater coils is calculated accordingly to Equation 6. As a function of the heater power these losses add up to 12 Watt. During measurement evaluation this value is subtracted from the power meter reading.

Equation 7:

$$\dot{Q}_{\mathrm{HL\_el}} = 3 \times \dot{Q}_{\mathrm{cable}} + 30 \times \dot{Q}_{\mathrm{Coil\_inactive}}$$

with

$$\dot{Q} = P = I^2 \times R$$

with

$$R_{Conductor} = \frac{\rho \times L}{A}$$

$$\dot{Q}_{HL\_el} = 3 \times \; I_{Cable}^{2} \times \frac{\rho_{CU} \times L_{Cable}}{A_{Cable}} + 30 \times \; I_{Coil}^{2} \times \frac{\rho_{Fe} \times L_{Coil}}{\times A_{Coil}}$$

The connection line between power meter and heater connection box including both side feeder clamps have been screened for hot spots or insufficient electrical contacts causing heat losses to the environment. There was no heat loss found to be evident.

Heat loss due to a temperature drift of the whole bypass facility

Any change in the inlet temperature respectively of the mass flow entering the bypass provokes a temperature change of the whole measurement bypass including the MS. In order to compensate steady effects, the slope of a drift is determined by a linear fit. Based on the slope of this fit, the MS hardware mass and its specific heat capacity, the power needed to change the temperature of the MS is calculated according to Equation 8.

Equation 8: $$\dot{Q}_{\mathrm{HL\_DRIFT}} = m_{\mathrm{MS}} \times c_{p,\mathrm{MS}} \times \frac{\Delta\vartheta}{\Delta t}$$

Respecting the slope sign this heat flow is either added or subtracted from the measured heater power.

5. Results / Conclusion

All uncertainties contributing to the combined measurement uncertainty of the heat capacity measurement, estimations or information from manufacturers have been reviewed (Chapter 4). Relating to earlier heat capacity measurement results denoted with similar relative deviations to the real water value, compensating influences in the combined measurement result were identified and reduced to a level where a reliable repeatability and significance was achieved (see Figure 19).

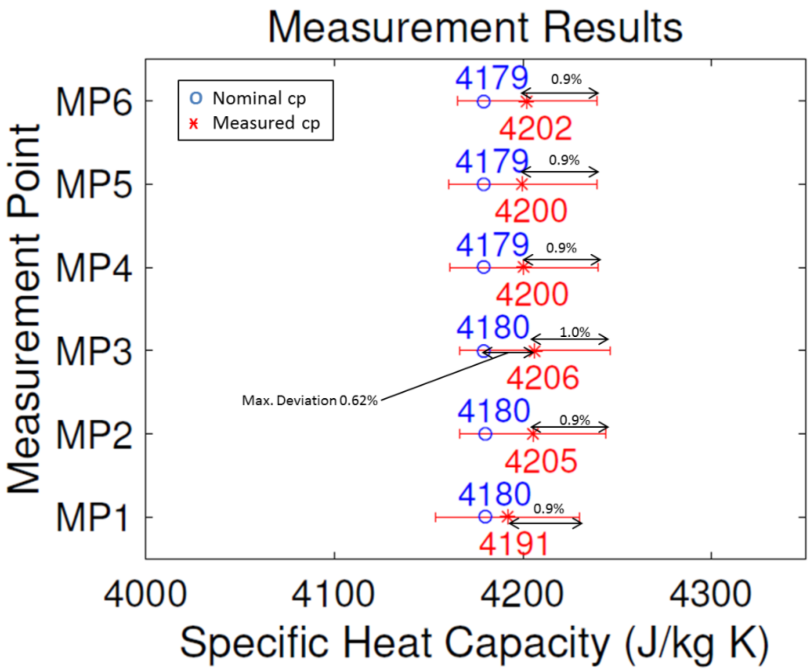

Figure 19: Heat capacity measurement of water, six measurement points of one hour each. The relative deviation from the real value and the combined measurement uncertainty are indicated by arrows

During the course of this task above mentioned investigations led to a variety of technical and analytical improvements which were always accompanied by repeated validation measurements.

One can see an obvious systematic deviation of the bypass reading (combined measurement result) to the known heat capacity of water. This deviation could not be reduced any further but still heat capacity measurement results are very accurate.

As the outcome of this activity, the overall combined measurement uncertainty of the c_p-measurement bypass was proved to be 1.0 % at mean operation temperatures between 25 and 60 °C. In addition, a detailed understanding of all uncertainty components and their combination was achieved and documented. There remains still a small systematic deviation of the bypass reading to the known heat capacity of water which could not be reduced further. However, the heat capacity is measured very accurately for a field measurement technique and fulfills the high standards of CSP testing. The aim of this task has been reached.

Gained knowledge is indispensable for any high precision heat capacity measurements of heat transfer fluids at temperatures up to 350 °C. It will be applied during the course of the SFERA II project during the heat capacity measurement of the HTF at the KONTAS facility at PSA.

List of publications

[Hilgert 2012] Christoph Hilgert, Gregor Bern and Marc Röger (2012) Kontas-CP - Flow Through Calorimeter for Online Heat Capactiy Measurement of Thermal Oils in CSP Application, SolarPACES 2012, Marrakesch (Marokko)

[Nicholas 2001] J.V. Nicholas and D.R. White (2001) Traceable Temperatures, John Wiley & Sons, Ltd, Print ISBN 0-471-49291-4, Electronic ISBN 0-470-84615-1, Page 137

[DKD 2003] Deutscher Kalibrierdienst Akkreditierungsstelle (2003) Richtlinie DKD-R 5 - Kalibrierung von Widerstandsthermometern, www.dkd.eu, Page 7

[IAPWS 1997] The International Association for the Properties of Water and Steam, IAPWS IF97 standard formulation,

List of abbreviations and definitions

CSP	Concentrating Solar Power
Delta	Difference, e.g. Delta T=T2-T1
DIN	Deutsches Institut für Normung, German Institute for Standardization
DIN EN	Standard from EN borrowed by DIN
DKD	Deutscher KalibrierDienst (German Calibration Service)
DKD-R	Richtlinie des DKD (Guideline by the DKD)
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DoW	Description Of Work
EN	Europäische Norm (European Committee for Standardization)
GUM	Guide to the expression of Uncertainties in Measurement
HTF	Heat Transfer Fluid
IR	InfraRed
ITML	Inlet Temperature Measurement Location (see Figure 2)
KONTAS	Konzentrator-Teststand Almería Spanien (Concentrator test facility Almería Spain)
KONTAS-c_p	Equipment for measuring the c_p value of different HTFs as part of the KONTAS project
MS	Measurement Section (see Figure 2)
OTML	Outlet Temperature Measurement Location (see Figure 2)
PID controller	Proportional-Integral-Derivative controller
PRT	Platinum Resistance Thermometer
PSA	Plataforma Solar de Almería
PT100	PRT with resistance R = 100 Ohm
SFERA II	Solar Facilities for the European Research Area - Second Phase
Sylterm 800	Brand name for a silicon oil based HTF
Therminol VP1	Brand name for a silicon oil based HTF
TML	Temperature Measurement Location
u(*x*)	Uncertainty in the determining of *x* with 2σ confidence interval
Uncertainty of type A	random uncertainty
Uncertainty of type B	systematic uncertainty
UPS	Uninterrupted Power Supply
WP 11	Work Package 11