Steady state criteria for parabolic trough receiver heat loss measurements

Cite as: AIP Conference Proceedings **2445**, 100005 (2022); https://doi.org/10.1063/5.0085918
Published Online: 12 May 2022

Johannes Pernpeintner and Björn Schiricke

Steady State Criteria for Parabolic Trough Receiver Heat Loss Measurements

Johannes Pernpeintner[1, a)] and Björn Schiricke[1, b)]

[1] *German Aerospace Center DLR e.V., Institute of Solar Research, Linder Hoehe, 50677 Koeln, Germany*

[a)] Corresponding author: johannes.pernpeintner@dlr.de
[b)] bjoern.schiricke@dlr.de

Abstract. Heat loss of parabolic trough receivers is measured in the laboratory at Steady State. Criteria for the Steady State shall ensure sufficient stabilization of the measurands without being excessive. The IEC TS 62862-3-3:2020 provides such criteria. This paper presents a model for the assessment of Steady State criteria in heat loss tests. Assuming constant heating power, lumped heat capacity and linearized heat loss, the model shows, that the IEC TS 62862-3-3 allows for significant deviations at low temperatures and large heat capacity. For the investigated configuration of low heat loss and large heat capacity, the model shows allowed deviations of 12.6 K at 100 °C, 5.5 K at 200 °C and 2.5 K at 300 °C. The paper discusses the weaknesses of Steady State criteria in the IEC TS 62862-3-3 and proposes to clarify the meaning of ± 0.5 K and ± 1% and, to expand the stabilization period to 60 minutes for measurements below 300 °C and to limit the scope of the standard to measurements > 240 °C.

INTRODUCTION

In every solar thermal power plant, the receiver is the central component that converts the concentrated radiation to thermal energy. Specifically, in parabolic trough plants a large number of receivers of 4 m to 5 m length are connected in series and situated in the focal line of the collector. The heat transfer fluid, oil, solar salt or water, flows through the absorber tube, a steel tube of 70 mm to 90 mm in outside diameter. The outside surface of the absorber is coated with a selective coating with high solar absorptance and low emittance at operating temperature. The absorber is enclosed by a glass envelope, and the annulus sealed air-tight and evacuated to suppress heat transfer via gas. Elements of that seal are the bellow and the glass-to-metal-seal, both important to compensate differential thermal expansion of the glass envelope and steel absorber.

An important property of the receiver is heat loss at operating temperature. Due to the size of parabolic trough receivers, heat loss can be measured with laboratory test benches [1-5]. In early 2020 the IEC TS 62862-3-3 was published standardizing these measurements. In laboratory heat loss tests the parabolic trough receiver is heated with electrical means to the temperature of interest between 100 °C and 550 °C. Usually cartridge heaters inserted into the absorber, compare Figure 1 and Figure 2. In Joule-heating electrical current is directed directly through the absorber. This paper focusses on cartridge heater systems as it is more common, however findings can be extended to Joule-systems.

At the ends of the receiver adiabatic conditions are created in the testbench by thermal insulation and counter heating. Homogeneity of absorber temperature in longitudinal direction is improved by additional heaters under the bellow, compare Figure 1. Often homogenization tubes from copper, brass, or aluminum between cartridge and absorber are employed to enhance homogeneity, especially in circumferential direction. The temperature of the absorber is measured with multiple thermocouples pressed against the inner surface of the absorber. As there is a temperature gradient from heater to homogenization tube to absorber, a temperature difference from thermocouple to absorber must be considered and should be corrected for [1]. The mean absorber temperature is calculated from multiple measurement positions. In this paper, only mean absorber temperature T is considered.

SolarPACES 2020
AIP Conf. Proc. 2445, 100005-1–100005-8; https://doi.org/10.1063/5.0085918
Published by AIP Publishing. 978-0-7354-4195-8/$30.00

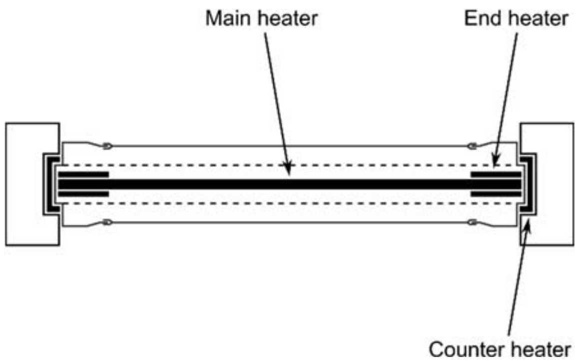

FIGURE 1. Heater configuration of heat loss testing with cartridges

FIGURE 2. Photograph of heater with thermocouples and convection shields at end heaters

Two methods are employed to achieve the Steady State at the target temperature: Constant power or closed-loop controller, compare Figure 3. Applying constant power, the temperature approaches the Steady State temperature asymptotically from higher or lower temperature depending on the previously measured temperature. Switching between constant power phases is initiated manually or with programmed switching-schedules. In general, closed-loop-controllers are often used for heating applications. They allow for a quick approach to Steady State and automatic temperature-keeping. However, for this specific application closed-loop-controllers introduce challenges: Controllers usually need some tuning to the system for good performance. However, in heat loss measurements system properties change significantly over the temperature of interest of 100 °C to 550 °C. A closed-loop controller out of tune can be sluggish or unstable. Hence, constant power heating is still in use for these measurements, as it offers reduced complexity in operation.

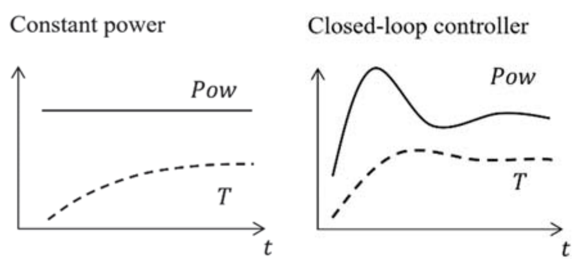

FIGURE 3. Stylized graphs of power and temperature vs. time for heat up method constant power and closed-loop controller

In practice the question arises, at which time one can consider the system to be in Steady State and start recording the data that will be used for evaluation. This data is then averaged over that period in order to obtain the Steady State properties. As temperature and heating power contain measurement noise, an ideal Steady State can never be reached - irrespective of the heating method. Hence, criteria must define the Steady State for the experiment. Different types of criteria have been proposed: A straight forward criterion is to define a maximum interval of temperature and power within a certain time period. At DLR is was found quite useful to quantify the approach to steady state by real time observation of slope and curvature of temperature described by 1st and 2nd-order derivatives $\dot{T}(t),\ \ddot{T}(t)$.

In general criteria for the Steady State must also be strict enough so that the evaluation yields results with the required accuracy. At the same time, they shall not be excessively strict allowing for a reasonably fast measurement and tolerating some measurement noise and small term instabilities. It must also be anticipated that formalized criteria - written down in a standard - are implemented in test bench control programs for automatic switching at the earliest time possible to the next temperature step either to save measurement time or to pull the result in a certain direction within the allowed limits. It must be expected that allowed tolerances are used to capacity.

The IEC TS 62862-3-3 contains criteria for the Steady State in heat loss measurements of parabolic trough receivers. Those criteria considered relevant in this discussion are a maximum deviation of absorber temperature T of ± 0.5 K and of heating power Pow of ± 1 %. That criteria can be applied to a simple moving average of 1 minute of the measured raw data in order to reduce the impact of measurement noise. While the criteria must be fulfilled for two periods, a stabilization period and for an evaluation period in direct succession, only data of the evaluation period is used to calculate the measurement result. Regarding the duration of both periods the technical specification is confusing: Page 12 lists for the evaluation periods minimum durations between 15 and 240 minutes depending on absorber temperature. This page does not mention any stabilization periods. Page 13 requires a stabilization period of 30 minutes and an evaluation period of 15 minutes. In the following conditions of page 13 of 30 and 15 minutes are assumed, as this represents the easier criteria for low temperatures and hence represents a worst case, if chosen by a laboratory.

Secondly the wording of the IEC TS 62862-3-3 is unclear. On page 13 it requires '± 0.5 K' for both periods. In fast systems with large measurement noise the interpretation might appear not that important, but in slow systems with low noise, especially with constant power heating, the exact meaning becomes important. In that case temperature approaches Steady State in a slow drift with shallow curvature. In Figure 4 these four schematics with constant slope show the impact of two additional aspects, that are not clearly defined in the technical specification:

1. If the criterion of ± 0.5 K shall be valid for both periods, does it mean, that each period is evaluated individually, or does it mean, that the limiting borders shall be the same for both periods?
2. Does '± 0.5 K' mean, the difference between minimum and maximum temperature in the period must not be greater than 1 K, or does the symbol ± indicate an upper and lower limit deviating from a mean? The notation is similar to that of uncertainties. If it is the deviation to a mean, the deviation from which mean? The most relevant mean is that of the evaluation period!

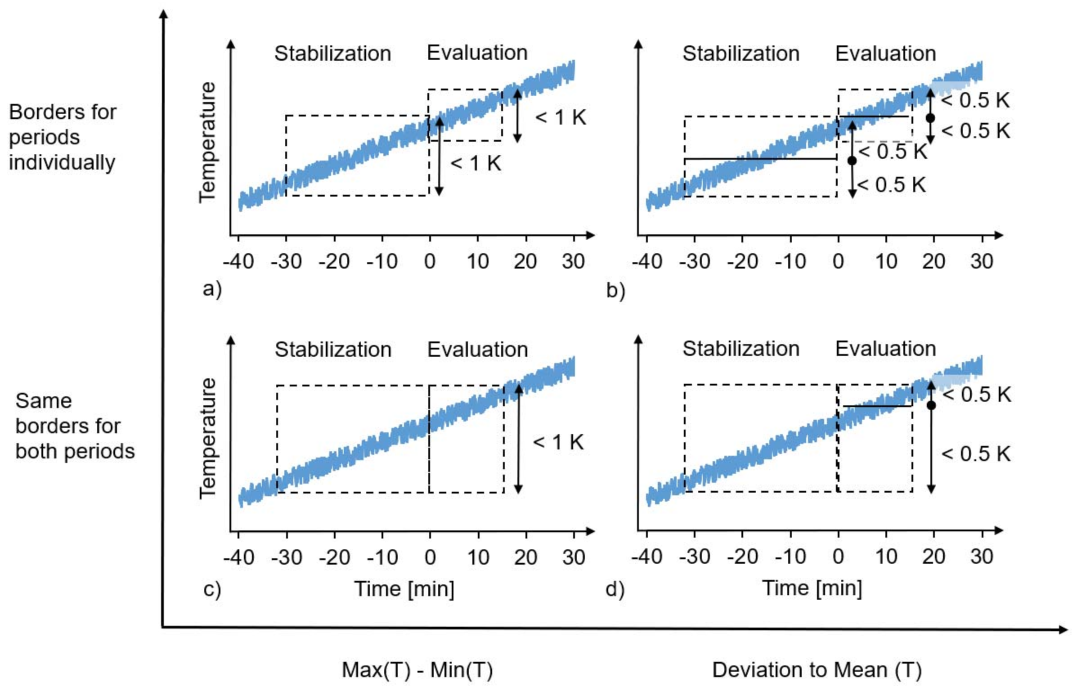

FIGURE 4. Interpretations of '± 0.5 K' in the case of low noise with constant temperature drift

While the assumption of constant slope might only be a reasonable approximation for slow systems, it allows for a quick quantitative assessment of the different cases shown in Figure 4 in these conditions. In case a) both periods can have a drift of 1 K – assuming negligible noise. With constant temperature slope, only the stabilization period is relevant, as it is the longer of both periods, and the maximum allowed slope is 1 K/(30 min) = 2 K/h. Similar analysis yields for case b) 2 K/h, for case c) 1.3 K/h and for case d) 0.8 K/h. Hence, depending on the interpretation of the borders in reading the IEC TS 62862-3-3, the criterion in that situation changes by a factor of 2.5.

MODEL - HEAT-UP WITH CONSTANT POWER

For a more robust assessment the Steady State criteria are investigated in the following with regards to the potential deviation of the measurement result compared to the situation of the ideal Steady State. In terms of temperature deviation that means we are interested in the difference between measured Steady State temperature and temperature at ideal Steady State $T_{ss,m} - T_{ss}$. In this paper the model is developed for the case of constant power heating, so the power criterion of ± 1 % is not assessed in this model.

Main reason for investigating the constant power heat-up is, that the dynamics is much easier to capture compared to the system with closed-loop controller as for the second the dynamics depends on hardware, controller type, and controller parameters.

Developing the new model, it is not the aim to perfectly model an existing system, but to find fundamental relationships impacting the accuracy of the measurement. Hence, in addition to limiting the scope to the constant power case, the model furthermore contains several approximations in order to simplify mathematics while preserving the essential behavior. This way a fully analytical model is developed in the following:

The first approximation in the model is a lumped-heat approximation, compare Figure 6.

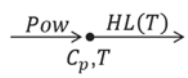

FIGURE 5. Lumped heat model

In the model the absorber, homogenization tube, and heater rod are assumed as one single element. Lumping together these elements to one heat capacity C_p with one equal temperature T is motivated by the fact that the largest resistance for the heat flowing outwards is that via the receiver annulus between absorber and glass by design. This annulus is optimized for low thermal conduction through evacuation of the annulus and application of a selective coating at the absorber. Compared to that the components inside the absorber are thermally well connected to the absorber. Hence, the internal structure of the absorber is not resolved here. As there is only one element, the dynamics are given by the heat flow into the element, the power introduced by the electrical cartridge heater Pow and heat loss of the system $HL(T)$. The system can be described by the differential equation

$$\frac{dT}{dt} = \frac{1}{C_p}(Pow - HL(T)) \tag{1}$$

where $\frac{dT}{dt}$ is the rate of change of absorber temperature. As heat loss $HL(T)$ in parabolic trough receivers is dominated by radiation via the annulus, heat loss $HL(T)$ of parabolic trough receivers is often described as function of absorber temperature, not as function of temperature difference to ambient. This approach is also chosen here.

Since we are interested in describing the approach of the system to the ideal Steady State temperature T_{ss}, heat loss $HL(T)$ is linearized near T_{ss} by

$$HL(T) = A + B \cdot T \tag{2}$$

using the parameters A and B. It directly follows from Equation 2 and constant heating power $Pow = const$ at ideal Steady State temperature T_{ss}

$$HL(T_{ss}) = Pow = A + B \cdot T_{ss}. \tag{3}$$

Inserting Equation 2 and Equation 3 into Equation 1 and introducing the time constant $\tau = C_p/B$ the differential equation is

$$\frac{dT(t)}{dt} = \frac{1}{\tau}(T_{ss} - T(t)) \tag{4}$$

This differential equation can be solved assuming starting conditions $T(t = 0) = T_0$ by an exponential approach to ideal Steady State temperature by

$$T(t) = T_{ss} + (T_0 - T_{ss}) \cdot e^{-\frac{t}{\tau}}. \tag{5}$$

Temperature drift $\dot{T}_0$ at time $t = 0$ can be derived either from Equation 4 or by differentiation of Equation 5 to

$$\dot{T}_0 = (T_0 - T_{ss}) \cdot \left(-\frac{1}{\tau}\right). \tag{6}$$

Equation 6 is a simple, direct relationship between temperature slope $\dot{T}_0$, the time constant τ, and the deviation of temperature from ideal Steady State temperature $(T_0 - T_{ss})$. Using the allowed temperature slope according to IEC TS 62862-3-3 and the analysis in the previous chapter and calculated time constants, we can determine allowed deviations from ideal Steady State temperatures.

The result of the measurement at for temperature $T_{ss,m}$ at Steady State according to the IEC TS 62862-3-3 is mean temperature during the evaluation period. Hence, another useful relationship for evaluating the criteria is the mean of the temperature, that can be derived by integration of Equation 5 and scaling by

$$\bar{T}(t) = \frac{1}{t}\int_0^t T(t')\, dt' = T_{ss} + (T_0 - T_{ss}) \cdot \frac{\tau}{t} \cdot \left(1 - e^{-\frac{t}{\tau}}\right) \tag{7}$$

RESULTS

First, typical time constants are calculated. As large time constants correlate to large deviations, according to Equation 6, a configuration with large heat capacity C_p and small slope B of heat loss curve $HL(T)$ is investigated, compare Equation 2, as this is the most critical configuration. The estimation of heat capacity C_p is presented in more detail in the appendix. A generic configuration shall be investigated here, hence, several simplifications are made with respect to included components, geometry, and assumed material properties. For example, only absorber, homogenization tube, and main heater are considered. For the chosen configuration the heat capacity is estimated to 19640 J/K, see appendix. Additionally, for the further investigation heat capacity C_p is assumed to be independent of temperature.

Assumed heat loss HL(T) for the receiver is shown in Table 1 and Table 2. From heat loss the slope B is derived by fitting to a polynomial and derivation with respect to temperature.

Criteria shall be evaluated in two ways, compare Table 1 and Table 2: The evaluation according to Table 1 follows the introductory chapter in translating the criteria of IEC TS 62862-3-3 to maximum temperature slopes and subsequent evaluation of the model according to Equation 6. It shall be repeated, that in the first step constant slope is assumed, while in the 2nd step it is not. As the heat-up curve according of the model is know exactly in form of the exponential approach to steady state, the criteria of IEC TS 62862-3-3 can also be evaluated mathematically exact using Equation 5 and Equation 7. Both ways of evaluation shall be presented here, as – we will see in the results – the approach assuming constant temperature rate in evaluation of the IEC TS 62862-3-3 criteria provide reasonable accuracy for large time constants but much easier usage.

Table 1 shows the result of the first approach. Only the cases of 2 K/h (Figure 4 a) and 0.8 K/h (Figure 4 d) are shown. T_0 indicates the temperature, at which the criterion of IEC TS 62862-3-3 translated to the maximum slope is fulfilled. Hence, $T_0 - T_{ss}$ is the temperature deviation from ideal Steady state, when the criterion is fulfilled.

Second, the criteria of the IEC TS 62862-3-3 are evaluated mathematically exact using the equations of the model. The temperature follows an exponential approach and the exact measured temperature $T_{SS,meas}$ as calculated as a mean over the evaluation period is calculated applying the Equation 5 and Equation 7. Again Table 2 shows the cases a) and d) of Figure 4. Hence, the deviation from ideal Steady State is $T_{SS,m} - T_{ss}$. Results are shown in Table 2.

Both tables show, in addition to the deviation of measured temperature to ideal Steady State the heat loss equivalent to that temperature deviation ΔHL. ΔHL is given as fraction of heat loss $\Delta HL/HL$ calculated by $\Delta HL = (T_0 - T_{ss})/B$ in Table 1 and $\Delta HL = (T_{SS,m} - T_{ss})/B$ in Table 2.

TABLE 1. Allowed deviation for the generic measurement configuration with 19640 J/K using approximation of constant temperature rates

				Figure 4 a), 2.0 K/h		Figure 4 d), 0.8 K/h	
T_{ss} in °C	HL in W	B in W/K	τ in min	$T_0 - T_{ss}$ in K	$\Delta HL/HL$ in -	$T_0 - T_{ss}$ in K	$\Delta HL/HL$ in -
100	28	0.8	400	**13.3**	38.5 %	**5.3**	15.4 %
200	141	1.7	188	**6.3**	7.7 %	**2.5**	3.1 %
300	362	3.4	96	**3.2**	3.0 %	**1.3**	1.2 %
400	807	7.0	47	**1.6**	1.4 %	**0.6**	0.5 %
500	1696	13.5	24	**0.8**	0.6 %	**0.3**	0.3 %
550	2402	18.3	18	**0.6**	0.5 %	**0.2**	0.2 %

TABLE 2. Allowed deviation for the generic measurement configuration based on mathematically exact evaluation of the model

				Figure 4 a), exact		Figure 4 d), exact	
T_{ss} in °C	HL in W	B in W/K	τ in min	$T_{SS,m} - T_{ss}$ in K	$\Delta HL/HL$ in -	$T_{SS,m} - T_{ss}$ in K	$\Delta HL/HL$ in -
100	28	0.8	400	**12.6**	36.4 %	**5.1**	14.7 %
200	141	1.7	188	**5.5**	6.8 %	**2.3**	2.8 %
300	362	3.4	96	**2.5**	2.4 %	**1.0**	1.0 %
400	807	7.0	47	**1.0**	0.8 %	**0.4**	0.4 %
500	1696	13.5	24	**0.3**	0.2 %	**0.1**	0.1 %
550	2402	18.3	18	**0.2**	0.1 %	**0.1**	0.1 %

First observation of Table 1 and Table 2 is, that the time constant τ changes by a factor of 22 from 400 minutes at 100 °C to 18 minutes at 550 °C. This reflects the impact of the slope B of the heat loss curve on the dynamic behavior of the system, as the heat capacity is assumed constant for all temperatures. The time constant is the time the system needs to reduce the deviation to Steady State by $1/e$. Hence, comparing that time to duration of the stabilization time and evaluation time of 30 and 15 minutes shows, that the approximation of constant of temperature rate $\dot{T}$ for translation of the IEC TS 62862-3-3 to a maximum temperature rate is only a useful approximation at temperatures 300 °C and lower. This can also be seen by comparison of Table 1 and Table 2, where the temperature deviations to ideal Steady State for 100 and 200 °C are relatively close. For example, Table 1 at 100 °C case Figure 4 a) predicts 13.3 K, while 12.6 K is predicted by Table 2, a difference of 6%. The same case of Figure 4 a) shows for 550 °C a deviation of 0.6 K in Table 1 vs 0.2 K in Table 2, a difference of 400%.

Assuming the Steady State criteria shall limit the maximum deviation to 1 K or 1% in relative heat loss in order of magnitude, both tables suggests, that the criteria of IEC TS 62862-3-3 in the case of Figure 4 a) would be usable only for 400 °C and higher. With the strict interpretation of the criteria of IEC TS 62862-3-3 (case of Figure 4 d)) the deviations are acceptable at about 300 °C and higher.

DISCUSSION OF UNCERTAINTY

These results must be interpreted in context of the approximations of the model, evaluation and assumptions. As it is the intention of this investigation to estimate the order of magnitude of potential measurement deviations as a result of Steady State criteria, the uncertainties shall be discussed but – with one exception - not quantified.

The impact of assumption of constant temperature rate for the calculation of a maximum temperature rate has been assessed by comparing it to the exact solution in the form of Table 1 and Table 2. It can be seen, that both models have acceptable agreement for time constants larger than the stabilization and evaluation times. The lumped heat model doesn't resolve the internal structure of the heating system. In reality, as heat flows outwards, it transverses several objects and encounters additional thermal resistance. Hence, the model underestimates the time constants. The linearization of heat loss leads to deviations that depend on the temperature difference to steady state. The larger the deviation, the larger the error in that approximation. Compared to other uncertainties, however, the influence of this is assumed to be small. Assumptions for the receiver heat loss and system heat capacity were made - in tendency - to yield large time constants. However, as these assumptions were not unrealistic, the investigated example is still relevant. It goes without saying, that not in all test benches and not in all measurements the deviations are this high.

SUMMARY AND PROPOSED IMPROVEMENTS TO IEC TS 62862-3-3

This paper presented an investigation on the impact of Steady State criteria on heat los measurements of parabolic trough receivers. Currently the IEC TS 62862-3-3 defines such criteria. For the investigation of these criteria a model for constant power heating was developed and evaluated using assumptions for a low heat loss receiver and a cartridge heating system with homogenization tube. The model was evaluated using a mathematically exact approach and a simplified approach, both of which showed acceptable agreement for time constants larger than the duration of the criteria.

The evaluation showed, that the IEC TS 62862-3-3 currently allows deviations of 12.5 K at 100 °C, 5.5 K at 200 °C and 2.5 K at 300 °C for the investigated configuration.

Assuming that the criteria for Steady State in the measurement shall limit deviations to the ideal Steady State to the order magnitude of ± 1 K in temperature or ± 1% in measured heat loss the investigation shows that the IEC TS 62862-3-3 in its current form – allowing for a generous interpretation, the errors are larger than the threshold for measurements below 400 °C. Based on this investigation it is proposed to revise the IEC TS 62862-3-3 criteria. First, the language should be clarified, that ± 0.5 K and ± 1% refer to the mean of the evaluation period, or the measurement result. Typically heat loss measurements are performed at 250 °C and higher. Measurements at below 240 °C are relatively rare. Hence, it is proposed to increase the stabilization period for measurements between 240 and 290 °C to 60 minutes and remove measurements below 240 °C from the scope of the standard.

ACKNOWLEDGMENTS

We'd like to thank the Federal Ministry for Economic Affairs and Energy BMWi for supporting this work within the project QUARZ-Akkr Förderkennzeichen 03EE5033.

REFERENCES

1. J. Pernpeintner et al., AIP Conference Proceedings, (2017) 1850.
2. F. Burkholder and C. Kutscher, NREL-TR-550-42394 (2008).
3. F. Burkholder and C. Kutscher, NREL-TR-550-45633 (2009).
4. D. Lei et al., Energy Conversion and Management, (2013) 69 107-115.
5. S. Dreyer et al., Proceedings of SolarPACES Conferences, (2010), Perpignan, France.
6. IEC TS 62862-3-3:2020.
7. J. Pernpeintner and B. Schiricke, AIP Conference Proceedings, (2019) 2126, 120015.

APPENDIX

Estimation of Heat Capacity

For the estimation of the heat capacity the absorber, homogenization tube and heater are considered. Assumptions are shown in Table 3. Due to a lack of knowledge of internal structure of the heater rod the material parameters of steel are used. This is justified in this case, as, due to its low volume, the heater rod has only low impact on overall heat capacity and this investigation intends to investigate a generic configuration allowing for a coarse modelling.

Using the numbers given in Table 3, first volume, then mass, then heat capacity can be calculated.

The assumptions result a total heat capacity C_p of 19640 J/K, where 9600 J/K is the heat capacity of the absorber, 7640 J/K of the homogenization tube and 2400 J/K the heat capacity of the heater rod.

In the specific calculation performed for this paper, the intermediary result of mass is rounded to kg, (heater 5 kg, homogenization tube 20 kg, absorber 20 kg). Repeating the calculation without rounding for kg yields a total heat capacity of 19553 J/K. As a generic configuration is investigated, the difference of 0.5% is considered negligible.

TABLE 3. Estimation of heat capacity, assumptions and results

Property	**Value**	
Assumptions		
Absorber		
General:	Tube, steel	
Diameter	70	Mm
Thickness	2	Mm
Length	4060	Mm
Density	7850	kg/m^3
Specific heat capacity	480	J/(kg K)
Homogenization tube		
General	Tube, copper	
Diameter	50	Mm
Thickness	3.5	Mm
Length	4060	Mm
Density	8920	kg/m^3
Specific heat capacity	382	J/(kg K)
Main Heater		
General	Cylinder, steel	
Diameter	14	Mm
Length	4060	Mm
Density	7850	kg/m^3
Specific heat capacity	480	J/(kg K)
Results (using rounded mass)		
Heat capacity absorber	9600	J/K
Heat capacity homogenization tube	7640	J/K
Heat capacity heater	2400	J/K
→ Heat capacity, total	19640	J/K