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Calibration of an unloaded laboratory oven and the associated uncertainty of measurements

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ABSTRACT
The aim of this research was to describe the calibration of an unloaded laboratory oven used for drying textiles samples from respiration at (37 ± 2) °C and the detailed associated uncertainty of measurements. The calibration was performed at three temperature points (35 °C, 37 °C and 40 °C) in accordance with the DKD-R 5-7:2018 guidelines. The entire calibration system including the nine calibrated Pt100 temperature probes and the multimeter that reads temperature in °C was interfaced with a PC running a LabVIEW program for data acquisition and analysis. The temperature drift, inhomogeneity, instability and the calibration uncertainty were assessed. A small temperature drift of 0.3 °C over 48 hours at 40 °C was found. The temperature inhomogeneity expressed as the maximum absolute difference between the reference location and the other locations, Max $|T_{ref} - T_i|$ was found well below the acceptable accuracy of ± 2 °C. The temporal instability expressed as the maximum difference between the average and the temperature of each Pt100, Max $|\overline{T} - T_i|$ was also smaller than the acceptance limit, ± 2 °C of the textile test. The expanded uncertainty did not exceed ± 1.24 °C indicating a good oven calibration. This investigation revealed that the calibrated oven maintains good temperature drift, homogeneity and stability making it suitable for reliable textile testing.

Section: RESEARCH PAPER

Keywords: Oven; calibration; Pt100, inhomogeneity; instability; uncertainty

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1. INTRODUCTION

Laboratory ovens are fundamental instruments in various scientific disciplines, employed for drying, sterilization, curing, and numerous other temperature-controlled processes. Accurate and reliable temperature control within these ovens is crucial for ensuring the validity and reproducibility of experimental results. However, oven performance can degrade over time, leading to deviations from the desired temperature. To maintain confidence in the data generated, regular calibration of laboratory ovens is essential [1]. Previous work on oven calibration has established various methodologies. Some approaches involve using a calibrated reference thermometer to compare the oven set point with the actual chamber temperature [2].

Others explore the use of multiple thermometers placed at different locations within the oven to assess temperature uniformity [3]. Several factors can influence the accuracy of oven calibration. These include the quality and calibration status of the reference thermometer, sensor placement within the oven chamber, air circulation patterns, and oven loading conditions [4], [5]. Understanding these factors is vital for designing a robust calibration procedure.

Traceability of temperature measurements to the International System of Units (SI) is paramount for ensuring global consistency and comparability of scientific data [6]. The International Temperature Scale of 1990 (ITS-90) defines the practical temperature scale for scientific use, providing a framework for calibrating thermometers against primary reference standards maintained by national metrology institutes [7], [8]. This paper presents a method for the calibration of laboratory ovens, emphasizing the importance of traceability to the SI. We describe the detailed methodology employed, including the selection and placement of reference thermometers, the approach to assessing temperature inhomogeneity and instability and the data analysis process.

Figure 1. The oven to be calibrated (A), multimeter (B) and nine Pt100 (C).

Furthermore, the paper outlines the procedure for estimating the uncertainty associated with the calibration measurement results, allowing to quantify the confidence level in oven temperature data. This work builds upon existing knowledge of oven calibration by providing a comprehensive approach that addresses key factors influencing accuracy and uncertainty aiming to contribute to the robust and reliable use of laboratory ovens in scientific research.

2. MATERIALS AND METHODS

The drying oven under calibration was of model DAF-135 manufactured by Trade Raypa, Teresa, Spain. The nine standard Pt100 temperature probes, 50 mm were manufactured by RS Pro, Fort Worth, Texas, USA. The multimeter used to read the temperature was a product of Keithley, UK. They are shown in Figure 1.

2.1. The calibration procedure

Nine Pt100 standard thermometers were used for the calibration of an unloaded laboratory oven used for textile testing against respiration at (37 ± 2) °C. The inside working space of the oven (90 cm) was divided into three levels (top, middle and bottom) for temperature measurements. At the top level, four Pt100 sensors (1, 2, 3, 4) were positioned at each corner and each of them was installed 3 cm away from the sidewalls and the ceiling. In the middle level, Pt100 number 5 was positioned in the centre and was considered the reference location. At the bottom level, four Pt100 sensors (6, 7, 8, 9) were positioned in the corners and each of them was installed 3 cm away from the sidewalls and the bottom of the oven as shown by the schematic in Figure 2. Thus, nine temperature measurement points were to record the temperature inside the oven simultaneously at each of the three calibration temperatures, 35 °C, 37 °C and 40 °C. These Pt100 sensors were connected to a mustimeter of resolution 0.001 °C capable of reading the temperature of the nine sensors simultaneously in degree Celsius (°C). The entire measurement system was interfaced with a PC running a LabVIEW program for data acquisition and analysis. The oven was closed tightly before starting the calibration process so that the surrounding environmental conditions (21 ± 2) °C were of no effect on the oven temperature.

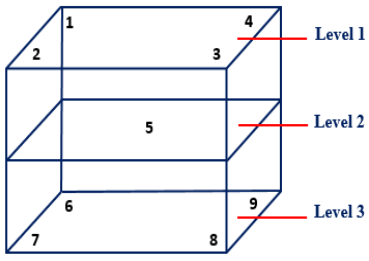

Figure 2. Schematic for positioning of the 9 Pt100 inside the oven.

To ensure the stability of temperature, the oven was run for 48 hours at the higher calibration temperature point, 40 °C. Once it reached stability, the temperature was set to 35 °C and left for 2 hours for stability, then the calibration started for one hour. Each of the nine Pt100 sensors was able to record the temperature every 5 seconds and the average of the values was calculated every 3 hours and recorded. The same calibration process was carried out at 37 °C and 40 °C.

2.2. The traceability of measurements

The traceability of the measurement results to the SI units was ensured by the calibration of the nine Pt100 temperature probes against a calibrated SPRT using a laboratory procedure accredited as per ISO/IEC 17025:2017.

3. RESULTS AND DISCUSSION

3.1. Temperature drift and stability

The temperature drift is defined as the continuous or incremental change over time in indication due to changes in metrological properties of a measuring instrument [6]. It is a measure of how much the temperature deviates from a desired setting over time. Excessive temperature drift can be a sign of some problems with the oven, such as malfunctioning of heating/cooling elements, poor insulation or inadequate air circulation. The amount of temperature drift can help determine how often the oven needs calibration. If the drift is small, calibrations can be spaced further apart and if it is significant, it may necessitate more frequent calibrations to ensure consistent and reliable temperature control. To ensure stability of the oven in the present calibration, the temperature was set at 40 °C for 48 hours continuously without changing the temperature set and the values measured simultaneously by the nine Pt100 sensors were recorded. The average of the measured temperature values by each thermometer was calculated at 3 hours intervals and the results were recorded in Table 1.

From these results, it can be seen that the maximum temperature is 39.636 °C by Ch 9 and the minimum is 39.323 °C by Ch 1. The temperature drift was calculated as the difference between these identified maximum and minimum temperatures and was found to be 0.313 °C over 48 hours. This drift value is much lower than the reported maximum acceptable drift of 1 °C, indicating good temperature stability in the working space of the oven [9]. On the other hand, the standard deviation reflects how spread out the temperature readings are during calibration. It ranges from 0.019 to 0.57, which is smaller than the uncertainty limit (± 2 °C) defined by the standard specification of the textile test indicating better stability [10]. Furthermore, the temperature results in Table 1 were represented graphically in Figure 3.

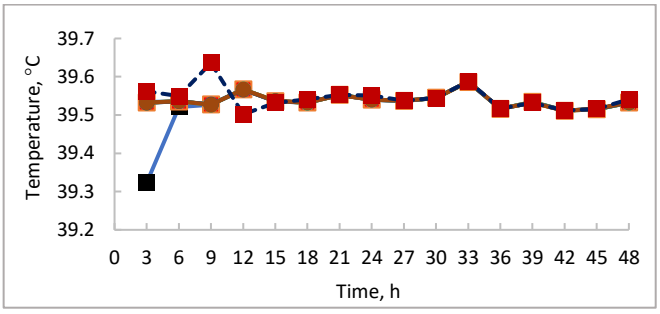

Figure 3. The temperature graph of the oven temperature drift at 40 °C by 9 Pt100 for 48 h.

Table 1. Temperature measurements for drift study of the oven at 40 °C.

Time, h	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	Ch 7	Ch 8	Ch 9
3	39.323	39.533	39.533	39.532	39.534	39.533	39.532	39.533	39.562
6	39.521	39.535	39.535	39.537	39.536	39.536	39.536	39.536	39.549
9	39.527	39.528	39.528	39.527	39.527	39.527	39.528	39.527	39.636
12	39.567	39.567	39.567	39.567	39.567	39.567	39.566	39.567	39.502
15	39.536	39.536	39.536	39.537	39.537	39.537	39.536	39.537	39.532
18	39.532	39.533	39.532	39.532	39.532	39.532	39.533	39.533	39.541
21	39.553	39.553	39.553	39.552	39.553	39.553	39.552	39.552	39.553
24	39.539	39.540	39.539	39.540	39.540	39.541	39.540	39.540	39.551
27	39.538	39.537	39.538	39.537	39.537	39.537	39.537	39.538	39.538
30	39.544	39.545	39.544	39.544	39.544	39.544	39.544	39.544	39.544
33	39.587	39.586	39.587	39.587	39.588	39.587	39.588	39.587	39.588
36	39.517	39.516	39.517	39.516	39.516	39.516	39.516	39.517	39.517
39	39.533	39.534	39.533	39.533	39.533	39.534	39.533	39.532	39.532
42	39.512	39.511	39.511	39.511	39.512	39.512	39.512	39.511	39.512
45	39.516	39.515	39.516	39.515	39.515	39.515	39.515	39.517	39.516
48	39.532	39.533	39.532	39.532	39.532	39.532	39.533	39.533	39.541
$\bar{x}$	39.524	39.538	39.538	39.537	39.538	39.538	39.538	39.538	39.545
SD	0.057	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.032

3.2. Temperature inhomogeneity

The calibration results of the oven at 35 °C, 37 °C and 40 °C were corrected using the correction values reported in the calibration certificate of the Pt100 sensors then recorded in Table 2, Table 3 and Table 4 respectively. In these tables each column represents a measurement point at a specific location (Ch) within the oven chamber and each row represents the temperature readings at that location after a specific time interval in minutes. The mean of the temperature values measured by each Pt100 was calculated and then the grand mean of the nine means was calculated and considered as the measured value. The grand means were found to be 34.855 °C, 36.554 °C and 39.577 °C at the set temperatures 35 °C, 37 °C and 40 °C respectively and were recorded in the mentioned tables. From the calibration data in the above tables, the uniformity of temperature in the oven, which is essential for accurate and reliable calibration, was assessed in accordance with the DKD-R 5-7 [4]. The difference between the temperature of Pt100 in the reference location (Ch 5) and that of Pt100 in each location $|T_{\mathrm{ref}} - T_i|$ was calculated and the maximum deviation, Max $|T_{\mathrm{ref}} - T_i|$ along the calibration range was identified and reported in Table 5. According to the criterion in Equation (1)

$$|\delta T_{\mathrm{inhom}}| \leq |T_{\mathrm{ref}} - T_i| \tag{1}$$

the temperature inhomogeneity $|\delta T_{\mathrm{inhom}}|$ was found 0.820 °C, 0.912 °C and 0.887 °C at 35 °C, 37 °C and 40 °C respectively. These values came within the acceptance criteria of ± 2 °C specified by the test specification [10]. Thus, it can be concluded that the temperature inside the oven is sufficiently homogeneous for drying textile samples from respiration and the temperature differences, $|T_{\mathrm{ref}} - T_i|$ are unlikely to have a significant impact on the drying process.

The variation in the time of Max $|T_{\mathrm{ref}} - T_i|$ in Table 5 at the calibration temperatures, 35 °C, 37 °C and 40 °C can be attributed to a combination of factors. The different sensors may have varying thermal lag and response times to reach the desired temperature and stabilize compared to the reference sensor. This can lead to variations in the time at which maximum deviation occurs. The temperature gradient within the oven and the position of each sensor relative to these temperature gradients can influence its response time and deviation from the reference. In addition, the design of the oven including its insulation, ventilation system and heating element configuration may affect temperature uniformity and response time. It is also worthy to mention that the calibrated sensors might have inherent differences in accuracy and sensitivity, which can contribute to variations in the measured temperatures and the time of maximum deviation. These factors can interact and influence each other, leading to variations in the time of maximum deviation for different temperature settings.

3.3. Determination of temporal instability

Precise temperature control is crucial for ideal incubation, particularly for sensitive samples and procedures. The DKD-R 5-7 guidelines define how to measure an oven temporal stability, which reflects temperature fluctuations over time. Thermal instability is quantified as the Max $|T_{\mathrm{ave}} - T_i|$. The calculations were made using the temperature values measured by the nine Pt100 sensors for at least 30 minutes after the oven reached stability in case of each calibration temperature. The largest difference was identified for each sensor at each calibration temperature and recorded in Table 6. From this table, it can be concluded that the thermal instability values, $|\delta T_{\mathrm{instab}}|$, as defined by the criterion in Equation (2)

$$|\delta T_{\mathrm{instab}}| \leq |T_{\mathrm{ave}} - T_i| \tag{2}$$

are 0.303 °C, 0.348 °C and 0.334 °C at 35 °C, 37 °C and 40 °C respectively. These values are significantly lower than the acceptance criteria of ± 2 °C specified in the textile test specification, indicating a very good stability of the temperature calibration system [10]

3.4. The influence of radiation

The DKD-R 5-7 guideline [4] states that when the internal air temperature deviates from the surrounding room temperature, the oven inner walls will also have a different temperature than the air. However, objects within the usable volume will not reach the air temperature due to radiant heat transfer. The influence of radiation on temperature

Table 2. Calibration temperature results at 35 °C for 1 h.

Time, min	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	Ch 7	Ch 8	Ch 9
4	34.977	35.087	35.132	35.048	34.452	34.807	35.072	34.952	34.753
8	35.129	35.139	34.844	34.803	34.565	34.947	34.975	34.970	34.769
12	34.841	34.898	34.960	34.944	34.469	34.964	35.078	35.121	34.923
16	34.950	35.037	34.861	34.956	34.570	35.113	35.119	34.833	34.634
20	34.845	35.046	34.963	35.103	34.596	34.816	34.889	34.943	34.744
24	34.957	35.195	34.988	34.800	34.383	34.938	35.016	34.835	34.636
28	34.982	34.894	34.772	34.927	34.509	34.831	35.022	34.944	34.746
32	34.762	35.018	34.901	34.822	34.518	34.932	35.175	34.978	34.780
36	34.891	34.913	34.908	34.923	34.667	34.970	34.880	34.748	34.550
40	34.902	35.016	35.056	34.960	34.373	34.736	34.994	34.877	34.680
44	35.046	35.054	34.759	34.727	34.484	34.868	34.891	34.882	34.686
48	34.753	34.814	34.874	34.860	34.380	34.874	34.989	35.035	34.837
52	34.870	34.955	34.776	34.870	34.485	35.031	35.037	34.749	34.548
56	34.773	34.964	34.886	35.029	34.535	34.746	34.809	34.866	34.666
60	34.877	35.124	34.936	34.742	34.303	34.858	34.948	34.773	34.572
Mean	34.904	35.010	34.908	34.901	34.486	34.896	34.993	34.900	34.701
Grand mean		34.855							
SD	0.106	0.104	0.104	0.111	0.097	0.104	0.099	0.106	0.106

Table 3. Calibration temperature results at 37 °C for 1 h.

Time, min	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	Ch 7	Ch 8	Ch 9
4	36.661	36.644	36.541	36.592	36.422	36.684	36.591	36.409	36.208
8	36.544	36.690	36.824	36.689	36.094	36.407	36.668	36.662	36.460
12	36.827	36.792	36.496	36.412	36.170	36.668	36.650	36.547	36.345
16	36.502	36.514	36.572	36.665	36.142	36.549	36.693	36.826	36.624
20	36.574	36.766	36.546	36.549	36.199	36.827	36.791	36.503	36.299
24	36.549	36.649	36.604	36.830	36.293	36.502	36.521	36.575	36.374
28	36.600	36.930	36.696	36.505	36.018	36.573	36.770	36.552	36.349
32	36.690	36.605	36.421	36.571	36.271	36.549	36.650	36.605	36.404
36	36.420	36.673	36.671	36.552	36.150	36.605	36.933	36.696	36.494
40	36.669	36.654	36.555	36.605	36.432	36.702	36.608	36.420	36.217
44	36.560	36.708	36.830	36.704	36.112	36.416	36.670	36.670	36.469
48	36.829	36.809	36.515	36.412	36.170	36.668	36.654	36.563	36.358
52	36.511	36.511	36.571	36.667	36.151	36.553	36.697	36.828	36.627
56	36.570	36.767	36.551	36.556	36.199	36.829	36.805	36.511	36.310
60	36.556	36.661	36.604	36.830	36.306	36.518	36.515	36.573	36.372
Mean	36.604	36.692	36.600	36.609	36.209	36.603	36.681	36.596	36.394
Grand mean		36.554							
SD	0.114	0.110	0.113	0.125	0.116	0.127	0.110	0.124	0.124

Table 4. Calibration temperature results at 40 °C for 1 h.

Time, min	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	Ch 7	Ch 8	Ch 9
4	39.621	39.927	39.723	39.550	39.048	39.584	39.765	39.573	39.397
8	39.726	39.655	39.452	39.586	39.267	39.572	39.701	39.625	39.628
12	39.453	39.690	39.667	39.574	39.200	39.628	39.931	39.729	39.352
16	39.663	39.672	39.602	39.619	39.426	39.729	39.649	39.445	39.389
20	39.590	39.719	39.821	39.725	39.141	39.437	39.683	39.655	39.365
24	39.814	39.818	39.534	39.428	39.178	39.651	39.655	39.590	39.411
28	39.530	39.523	39.575	39.646	39.150	39.581	39.707	39.812	39.513
32	39.574	39.750	39.560	39.587	39.209	39.814	39.817	39.537	39.227
36	39.564	39.697	39.619	39.818	39.323	39.544	39.531	39.581	39.456
40	39.620	39.922	39.727	39.544	39.035	39.584	39.762	39.570	39.403
44	39.734	39.653	39.442	39.587	39.267	39.576	39.710	39.629	39.628
48	39.447	39.695	39.672	39.584	39.212	39.631	39.933	39.740	39.363
52	39.677	39.685	39.612	39.634	39.434	39.740	39.660	39.453	39.399
56	39.616	39.735	39.837	39.745	39.162	39.456	39.701	39.675	39.385
60	39.837	39.839	39.563	39.455	39.201	39.674	39.682	39.615	39.438
Mean	39.631	39.732	39.627	39.606	39.217	39.613	39.726	39.615	39.424
Grand mean		39.577							
SD	0.115	0.107	0.117	0.102	0.115	0.101	0.105	0.100	0.103

Table 5. The maximum deviation from the reference location Max $|T_{ref} - T_i|$ at 35 °C, 37 °C and 40 °C.

40 °C	37 °C	35 °C
$T_{ref} - T_2$	$T_{ref} - T_2$	$T_{ref} - T_2$
0.887 °C	0.912 °C	0.820 °C
at 40 min	at 28 min	at 60 min

measurements is negligible between 0 °C and 50 °C. Since the present oven calibration range was 35-40 °C, the impact of radiation was not determined. However, a conservative estimate of 0.3 K (0.3 °C) was added to the measurement uncertainty to account for potential radiation effects as indicated by the DKD-R 5-7 [4].

3.5. The uncertainty of measurements

The uncertainty in temperature measurements was estimated in accordance with ISO GUM [11] and DKD-R 5-7 [4] guidelines. The mathematical model for temperature correction is shown in Equation (3) from which the uncertainty sources were identified [4],

$$\Delta T_{\text{chamber}} = T_{\text{std}} - T_{\text{ind}} + \delta T_{\text{std}} + \delta T_{\text{inhom}} + \delta T_{\text{instab}} + \delta T_{\text{radiation}} + \delta T_{\text{load}} + \delta T_{\text{res}} + \delta T_{\text{env}}\,, \tag{3}$$

where

$\Delta T_{\text{chamber}}$ – temperature correction for the oven chamber
T_{std} – temperature measured by the standard thermometers at all measuring locations
T_{ind} – display of the standard thermometer
δT_{std} – uncertainty of the standard thermometer: $\delta T_{\text{std}} = \delta T_{\text{cal}} + \delta T_{\text{drift}} + \delta T_{\text{res,std}} + \delta T_{\text{heat}}$
δT_{inhom} – spatial inhomogeneity of the oven temperature
δT_{instab} – temporal instability of the oven temperature
$\delta T_{\text{radiation}}$ – radiation influence on the oven temperature
δT_{load} – load influence on temperature
δT_{res} – resolution of the standard thermometer
δT_{env} – environmental influence on temperature.

Since the present calibration was carried out for an unloaded oven, the effect of loading was not considered in the uncertainty budget. Also, the influence of ambient conditions in the present calibration is not relevant for the use of the oven in textile drying and therefore was not taken into consideration [4]. Hence, the sources of uncertainty contributing to the temperature measurements in the calibration process of the oven were presented in the fishbone structure in Figure 4 and their estimation is explained below.

3.5.1. The uncertainty of the standard, $u(\delta T_{\text{std}})$

The uncertainty of the standard $u(\delta T_{\text{std}})$ consists of four contributions. These are, calibration $u(\delta T_{\text{cal}})$, resolution $u(\delta T_{\text{res}})$, drift $u(\delta T_{\text{drift}})$ and self-heating $u(\delta T_{\text{heat}})$[4] . The $u(\delta T_{\text{cal}})$ was calculated by dividing the largest expanded

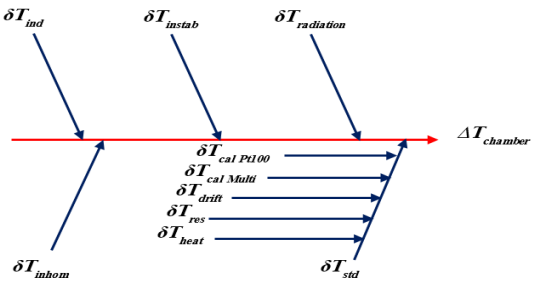

Figure 4. Fishbone structure showing the uncertainty sources.

uncertainty (0.17 °C) stated in the calibration certificate of the Pt100s by 2 according to Equation (4)

$$u(\delta T_{\text{cal}}) = \frac{U_{\text{exp}}}{2} \tag{4}$$

and was found to be 0.085 °C. The uncertainty of the multimeter calibration quoted in the certificate was 12 μΩ/Ω at 100 Ω. A sensitivity coefficient (α) of 0.4 Ω equivalent to 1 K was used to convert the resistance to a temperature unit [12]. Thus, the value 12 μΩ/Ω was converted to 30 μK (0.000030 °C) and was divided by 2 according to Equation (4) to obtain the standard uncertainty as 0.000015 °C

This multimeter uncertainty was combined with the Pt100 calibration uncertainty calculated earlier as $\sqrt{0.000015^2 + 0.085^2}$ °C to represent the $u(\delta T_{\text{cal}})$ contribution in Equation (5)

$$u(\delta T_{\text{std}}) = \sqrt{\begin{matrix}[C_1 \cdot u(\delta T_{\text{cal}})]^2 + [C_2 \cdot u(\delta T_{\text{res}})]^2 \\ +[C_3 \cdot u(\delta T_{\text{drift}})]^2 \\ +[C_4 \cdot\ u(\delta T_{\text{heat}})]^2\end{matrix}}\,. \tag{5}$$

As for the resolution of the multimeter, which is 0.001 °C, uncertainty was calculated according to Equation (6) and was found to be 0.00029 °C

$$u(\delta T_{\text{res}}) = \frac{Resolution}{2\sqrt{3}}. \tag{6}$$

The drift of the Pt100 was considered 10 mK (0.01 °C) and the self-heating was considered 50 mK (0.05 °C) assuming a rectangular distribution according to the DKD-R 5-7 guidelines [4]. They were calculated using Equations (7) and (8) and were found to be 0.0058 °C and 0.029 °C respectively.

$$u(\delta T_{\text{drift}}) = \frac{0.01}{\sqrt{3}}\,°\text{C} \tag{7}$$

$$u(\delta T_{\text{heat}}) = \frac{0.05}{\sqrt{3}}\,°\text{C}. \tag{8}$$

These four uncertainty components were combined according to Equation (5) to provide the standard uncertainty $u(\delta T_{\text{std}})$ of the Pt100, where C_1, C_2, C_3 and C_4 are the sensitivity coefficients. Each of them equals 1 since the

Table 6. Maximum temperature difference $|T_{ave} - T_i|$ for the nine Pt100 at 35 °C, 37 °C and 40 °C.

Temp, °C	Max $\lvert T_{ave} - T_i \rvert$, °C								
	Ch 1	Ch 2	Ch 3	Ch 4	Ch 5	Ch 6	Ch 7	Ch 8	Ch 9
35	0.298	0.289	0.303	0.283	0.289	0.280	0.289	0.301	0.302
37	0.337	0.335	0.336	0.336	0.329	0.337	0.348	0.342	0.341
40	0.334	0.326	0.319	0.329	0.323	0.323	0.322	0.319	0.316

uncertainty contributions were expressed in °C [13]. The calculated $u(\delta T_{\mathrm{std}})$ value was found to be 0.086 °C.

3.5.2. The repeatability of measurements $u(T_{\mathrm{ind}})$

The type A uncertainty contribution was determined by dividing the standard deviation of the mean value for the indications of each Pt100 at each calibration temperature by the square root of n according to Equation (9), where n equals 15

$$u(T_{\mathrm{ind}}) = \frac{SD}{\sqrt{n}}. \tag{9}$$

The calculated values were reported in Table 2, Table 3 and Table 4. The obtained uncertainty values, 0.029 °C, 0.033 °C and 0.030 °C were found the largest at the calibration temperatures 35 °C, 37 °C and 40 °C respectively and were taken as the type A uncertainty.

3.5.3. The spatial inhomogeneity

The standard uncertainty associated with the spatial inhomogeneity was calculated by Equation (10)

$$u(\delta T_{\mathrm{inhom}}) = \frac{1}{\sqrt{3}} \cdot \mathrm{Max}(T_{\mathrm{ref}} - T_i) \tag{10}$$

using the three maximum temperature differences reported in Table 5 at 35 °C, 37 °C and 40 °C respectively. The resulting uncertainty values were found to be 0.47 °C, 0.53 °C and 0.51 °C assuming a rectangular distribution of the results.

Table 7. The uncertainty budget components at the calibration point, 35 °C.

No	Quantity (source)	Estimate x_i	Unit	Probability distribution	Standard uncertainty $u(x_i)$	Sensitivity coefficient, c_i	$c_i \cdot u(x_i)$
1	Standard (Pt100)	34.928	°C	Normal			
	- Calibration	0	°C	Normal	0.086	1	0.086
	- Drift	0	°C	Rectangular	0.0058	1	0.0058
	- Resolution	0	°C	Rectangular	0.00029	1	0.00029
	- Self-heating	0	°C	Rectangular	0.029	1	0.029
		u_{std}		0.086			
2	Indication	34.855	°C	Normal	0.029	1	0.029
3	Inhomogeneity	0	°C	Rectangular	0.474	1	0.474
4	Instability	0	°C	Rectangular	0.175	1	0.175
5	Effect of radiation	0	°C	Rectangular	0.173	1	0.173
The combined standard uncertainty, u_c				0.54			
The expanded uncertainty, U_{exp}		k = 2.069		1.12			

Table 8. The uncertainty budget components at the calibration point, 37 °C.

No	Quantity (source)	Estimate x_i	Unit	Probability distribution	Standard uncertainty $u(x_i)$	Sensitivity coefficient, c_i	$c_i \cdot u(x_i)$
1	Standard (Pt100)	36.926	°C	Normal			
	- Calibration	0	°C	Normal	0.086	1	0.086
	- Drift	0	°C	Rectangular	0.0058	1	0.0058
	- Resolution	0	°C	Rectangular	0.00029	1	0.00029
	- Self-heating	0	°C	Rectangular	0.029	1	0.029
		u_{std}		0.086			
2	Indication	36.554	°C	Normal	0.033	1	0.033
3	Inhomogeneity	0	°C	Rectangular	0.526	1	0.526
4	Instability	0	°C	Rectangular	0.201	1	0.201
5	Effect of radiation	0	°C	Rectangular	0.173	1	0.173
The combined standard uncertainty, u_c				0.60			
The expanded uncertainty, U_{exp}		k = 2.074		1.24			

Table 9. The uncertainty budget components at the calibration point, 40 °C.

No	Quantity (source)	Estimate x_i	Unit	Probability distribution	Standard uncertainty $u(x_i)$	Sensitivity coefficient, c_i	$c_i \cdot u(x_i)$
1	Standard (Pt100)	39.923	°C	Normal			
	- Calibration	0	°C	Normal	0.086	1	0.086
	- Drift	0	°C	Rectangular	0.0058	1	0.0058
	- Resolution	0	°C	Rectangular	0.00029	1	0.00029
	- Self-heating	0	°C	Rectangular	0.029	1	0.029
		u_{std}		0.086			
2	Indication	39.577	°C	Normal	0.030	1	0.030
3	Inhomogeneity	0	°C	Rectangular	0.512	1	0.512
4	Instability	0	°C	Rectangular	0.193	1	0.193
5	Effect of radiation	0	°C	Rectangular	0.173	1	0.173
The combined standard uncertainty, u_c				0.58			
The expanded uncertainty, U_{exp}		k = 2.069		1.20			

3.5.4. The spatial instability

The associated standard uncertainties with the spatial instability values were calculated by Equation (11)

$$u(\delta T_{\text{instab}}) = \frac{1}{\sqrt{3}} \cdot \text{Max}(T_{\text{ave}} - T_i) \tag{11}$$

using the Max $|T_{\text{ave}} - T_i|$ values 0.303 °C, 0.348 °C and 0.334 °C at 35 °C, 37 °C and 40 °C respectively as reported in Table 6. The resulting uncertainty values were found to be 0.18 °C, 0.20 °C and 0.19 °C assuming a rectangular distribution of the results.

3.5.5. The radiation effect

As it has been mentioned above, the radiation effect was not metrologically determined since the calibration range was below 50 °C and a maximum contribution of uncertainty was taken as 0.3 K (0.3 °C) with rectangular distribution as recommended by the DKD-R 5-7 [4]. The uncertainty was calculated by Equation (12) and was found to be 0.173 °C

$$u(\delta T_{\text{radiation}}) = \frac{0.3}{\sqrt{3}} \text{ °C}\,. \tag{12}$$

4. THE COMBINED STANDARD UNCERTAINTY

The combined standard uncertainty, u_{c} was calculated by propagation at each calibration temperature according to Equation (13)

$$u(\delta T_{\text{std}}) = \sqrt{\begin{matrix}[C_1 \cdot u(T_{\text{ind}})]^2 + [C_2 \cdot u(T_{\text{std}})]^2 \\ +[C_3 \cdot u(T_{\text{inhom}})]^2 \\ +[C_4 \cdot u(T_{\text{instab}})]^2 + [C_5 \cdot u(T_{\text{radiation}})]^2\end{matrix}}, \tag{13}$$

where C_1, C_2, C_3, C_4 and C_5 are the sensitivity coefficients and each of them equals 1 since the uncertainty contributions were expressed in °C [13].

The components of the uncertainty budget and their values at the calibration temperatures 35 °C, 37 °C and 40 °C were reported in Table 7, Table 8 and Table 9. The tables show that the probability distribution was normal for the indication values (Type A) and for the calibration of the Pt100 standard, because its calibration certificate indicates that the used coverage factor was 2 at 95 % confidence level. Meanwhile, the distribution of the rest of the uncertainty sources (Type B) was rectangular for which the divisor was $\sqrt{3}$.

Looking at the values of the components of the standard uncertainty budget in Table 7, Table 8 and Table 9, it can be noticed that the uncertainty value resulting from the temperature inhomogeneity is dominating the budget components. Therefore, according to the DKD-R 5-7, the coverage factor k cannot be 2 ($k \neq 2$) and should be calculated. To determine the appropriate k-value, the effective degrees of freedom (ν_{eff}) was calculated using the Welch–Satterthwaite Equation (14),

$$\nu_{\text{eff}} = \frac{u_{\text{c}}^4(y)}{\sum_{i=1}^{n} \frac{u^4(x_i)}{\nu_i}}, \tag{14}$$

where

ν_{eff} – effective degrees of freedom

Table 10. The calibration results of the laboratory oven.

Reference temperature, °C	Measured temperature, °C	Correction, °C	Expanded uncertainty, °C
34.928	34.855	0.073	1.12
36.926	36.554	0.372	1.24
39.923	39.577	0.346	1.20

u_{c} – the combined standard uncertainty

$u(x_i)$ – the uncertainty of each individual component

ν_i – the degree of freedom.

4.1. The coverage factor, *k*

The effective degrees of freedom, ν_{eff} were found to be 23.170, 22.431 and 22.552 at 35 °C, 37 °C and 40 °C respectively. From the *t*-table, the coverage factor, *k* values corresponding to these ν_{eff} values, at 95 % confidence level were found to be 2.069, 2.074 and 2.069.

4.2. The expanded uncertainty, U_{exp}

The expanded uncertainty, U_{exp} at 35 °C, 37 °C and 40 °C was calculated based on the standard uncertainty u_{c} multiplied by the calculated coverage factor *k* to provide a confidence level of approximately 95 % using Equation (15)

$$U_{\text{exp}} = k \cdot u_{\text{c}}(\Delta T_{\text{chamber}})\,. \tag{15}$$

The obtained U_{exp} values were found ± 1.12 °C, ± 1.24 °C and ± 1.20 °C as reported in Table 7, Table 8 and Table 9.

Based on these uncertainty calculations, the calibration results of the oven were expressed in Table 10 that shows the reference temperature, the measured temperature, correction and the expanded uncertainty in °C. On the other hand, the smaller correction value observed at 35 °C compared to 37 °C and 40 °C may be due to factors related to the temperature inertia and the oven response at that particular temperature as it can be seen from the values in Table 2.

5. CONCLUSIONS

An unloaded laboratory oven used for colour fasting of textiles against respiration at (37 ± 2) °C was calibrated at 35 °C, 37 °C and 40 °C using nine calibrated Pt100 standard thermometers in accordance with the DKD-R 5-7:2018 Guidelines. The oven exhibited good temperature stability throughout a 48-hour test with a low drift of 0.313 °C, which is well below the acceptable limit of 1 °C. The temperature inhomogeneity values within the oven chamber in the calibration range were 0.820 °C, 0.912 °C and 0.887 °C which are well below the ± 2 °C acceptance criteria indicating a good spatial homogeneity. Temporal stability was also found to be very good, with a maximum temperature fluctuation of 0.348 °C at 37 °C, significantly lower than the ± 2 °C acceptable limit. While the influence of radiation on temperature measurements was negligible due to the calibration range (35–40 °C), a conservative estimate was included in the uncertainty calculations. The expanded uncertainty of measurements ranged from ± 1.12 °C to ± 1.24 °C. This paper provides a reliable approach for calibration and uncertainty estimation of unloaded laboratory ovens and ensures a reliable and controlled environment for various applications, particularly drying textile samples at specified temperatures.

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