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High stability constant temperature chamber upgrade and its characterisation

***Abstract**. The paper presents the design of an upgraded thermostatic chamber. The system for measuring the temperature gradient and stability in the chamber volume is described. The procedure for calibration of temperature sensors, selection of measuring points, and the procedure for measuring the temperature distribution and its stability over time are presented. Exemplary measurement results are also presented and discussed.*

***Streszczenie.** W referacie przedstawiono konstrukcję zmodernizowanej komory termostatycznej. Opisano system do pomiaru gradientu i stabilności temperatury w objętości komory. Przedstawiono procedurę wzorcowania czujników temperatury, dobór punktów pomiarowych oraz procedurę pomiaru rozkładu temperatury i jej stabilności w czasie. Zaprezentowano i omówiono również przykładowe wyniki pomiarów. (**Modernizacja komory o wysokiej stabilności i stałej temperaturze oraz jej charakterystyka**)*

Keywords: thermostatic chamber, temperature measurements, temperature gradient
Słowa kluczowe: komora termostatyczna, pomiary temperatury, gradient temperatury

Introduction

To achieve high accuracy of measurements it is necessary to minimize factors that influence their accuracy. Temperature variability can significantly affect the value and stability of measurement results and therefore increase measurement uncertainty. Therefore, to achieve high measurement accuracy, it is necessary to stabilize the temperature. For this purpose, high stability thermostatic chambers are commonly used [1-3]. There are well-known commercial thermostatic chambers available, but the main disadvantage of these solutions is related to their high cost [4, 5]. Thus, the low-cost constant temperature chamber was previously designed [2]. The main disadvantage of the formerly proposed solution was related to the necessity of using a PC with a dedicated software for the process variable control and a lack of ability to force and control airflow inside the chamber. In this paper, the upgrading of the chamber design including a user-friendly control interface is presented. However, to fully characterise thermostatic chamber one should consider not only the temperature stability but also temperature gradient inside the chamber. Uneven temperature distribution inside the chamber can affect the parameters of the tested object or cause temperature differences between objects (if there is more than one object stabilized in the chamber). Such variances can alter measured value and increase measurement uncertainty. To determine the stability and temperature distribution in the thermostatic chamber, single or multi thermometer measurement systems are used.

In single system there is only one thermometer used. To characterize the stability, it is usually placed in the middle of chamber and the temperature is measured for required time (usually multiple hours or days) [2]. However, for temperature distribution measurements, temperature sensor has to be relocated from one measurement point to another. The advantage of such system, when temperature stability is measured, relays in essence on measurement of the temperature drift in time. Moreover, when a single thermometer is used the type B uncertainty can be omitted, and only type A uncertainty is considered which leads to high accuracy measurements of stability. However, in such approach temperature distribution measurements are very time consuming as it requires to move temperature sensor from one measurement point to another. After such action is taken it is required to wait for temperature to stabilise before measurement can be done. Any additional movement inside the chamber can affect temperature distribution especially if it is required to open the chamber in order to move the sensor. This can require, in case of multiple measurement points, multiple days of measurements to determine temperature distribution inside a thermostatic chamber.

Lengthy measurement of temperature distribution can be avoided if multiple thermometers system is exploited [6]. In such system multiple thermometers are used, one for each measurement point. Therefore, multiple measurements can be done at the same time. And if those measurements are done for sufficiently long time the measurement data can be also used to determine the temperature stability of the chamber. Yet, with such approach type B uncertainty has to be considered as multiple thermometers are used. It is possible to minimize type B uncertainty if, all sensors are calibrated relative to one of them before measurements and based on this calibration required corrections are applied to each sensor. In such approach what is measured is the difference between sensor readings, and since they are calibrated against each other this difference can be measured with high accuracy. In this paper multisensory system for temperature measurement is presented along with the corresponding characterisation results of the modernized thermostatic chamber.

Chamber design

The design of the chamber was previously described in [2]. A system update was introduced in order to simplify the operation of the chamber for the user. A user-friendly interface with an LCD touch screen was added in the front of the chamber (Figure 1). It employs a 3.5-inch LCD screen coupled with a resistive touch panel integrated into the front plate of the chamber using a custom 3D-printed adapter. The microprocessor controller supervising the temperature regulator and the user interface, was also developed based on an ESP-WROOM-32 microprocessor module. The user interface allows to set the target temperature inside the chamber, to display the time trend of its changes (in the form of a graph), and to start and stop the temperature stabilisation process. The LED indicators inform on the status of the stabilisation process. The remote control and monitoring of the PID temperature controller using an external PC is also still available.

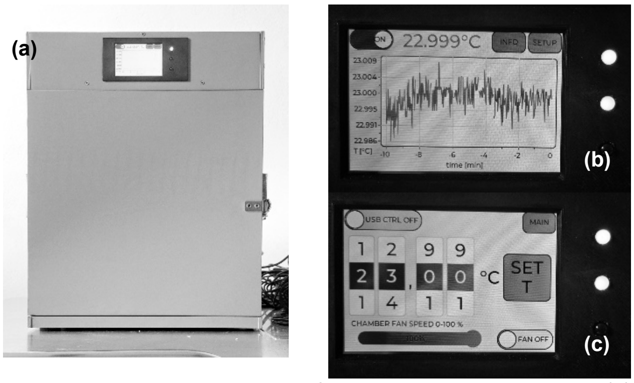

Fig. 1. The upgraded design of the thermostatic chamber (a) temperature variation graph (b) and set up options (c)

In addition, an electric fan was installed inside the chamber to force the air flow. The fan speed can be set with the LCD screen. Using the fan one can minimize time required to achieve temperature equilibrium inside the chamber, however in order to maintain temperature stability with highest accuracy it is recommended to turn off the fan during measurements.

Measuring equipment

In order to characterize chamber properties, it is necessary to measure its temperature stability (short-term and long-term) as well as temperature gradient in the chamber volume. To perform such measurements the system for measuring the gradient and stability of temperature in the discussed thermostatic chamber was developed. This system uses 30 Pt100 sensors, each connected via four-wire connection to an Agilent 34970A multi-channel meter. A PC with BenchLink Data Logger 3 software is used for data acquisition. Additionally, environmental conditions are monitored using a Label LB-701 thermo-hygrometer. All collected data have timestamps, allowing for later synchronization. A series of measurements from all sensors can be taken every 20 seconds - this is the shortest possible time due to the large number of sensors.

Temperature measurement system calibration

The developed measurement system is a multiple thermometers system. To minimize type B uncertainty, all sensors were calibrated against one of them before measurements were taken. This allows for precise determination of measurements differences between the sensors and the application of mathematical corrections. For this purpose, the sensors were placed in matching holes drilled in a cylindrical aluminium block (Fig. 2), which was located inside a thermostatic chamber. Additionally, precise sensor thermometer Dostmann P795 was used to monitor the temperature stability of the aluminium block. Before taking measurements, the temperature of the block located in the chamber was stabilized at (23.00±0.01)°C for 24 hours.

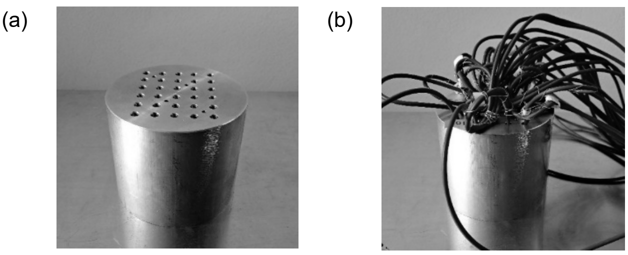

Fig. 2. Aluminium block for Pt100 thermoresistor calibration (a) general view, (b) populated with sensors

The temperature measurement results for all sensors are presented in Figure 3. The uncertainties, due to their small values, are not distinctly visible.

The sensor number 203, which displayed a temperature close to the average temperature (see Fig. 3) and the lowest type A uncertainty, was chosen as the reference one. Then, the average temperatures and type A uncertainty were calculated for the following 6h long measurement period. The corrections ΔT_i for sensors were calculated as:

(1) $$\Delta T_i = \overline{T}_{203} - \overline{T}_i,$$

where $\overline{T}_i$ is the average temperature for the i-th sensor, and $\overline{T}_{203}$ is the average temperature for the “reference” sensor number 203. The corresponding corrections for each of the 30 Pt100 sensors were listed in Table 1.

Table 1 The corrections for each sensor

Sensor No.	101	102	103	104	105
ΔT, °C	0.022	0.068	0.010	-0.003	0.018
Sensor No.	106	107	108	109	110
ΔT, °C	-0.032	0.048	0.038	-0.136	-0.012
Sensor No.	201	202	**203**	204	205
ΔT, °C	-0.085	0.001	**0**	0.004	-0.027
Sensor No.	206	207	208	209	210
ΔT, °C	0.001	-0.007	0.034	0.014	-0.084
Sensor No.	301	302	303	304	305
ΔT, °C	0.025	-0.033	-0.004	-0.031	-0.018
Sensor No.	306	307	308	309	310
ΔT, °C	-0.023	-0.011	0.038	0.045	-0.074

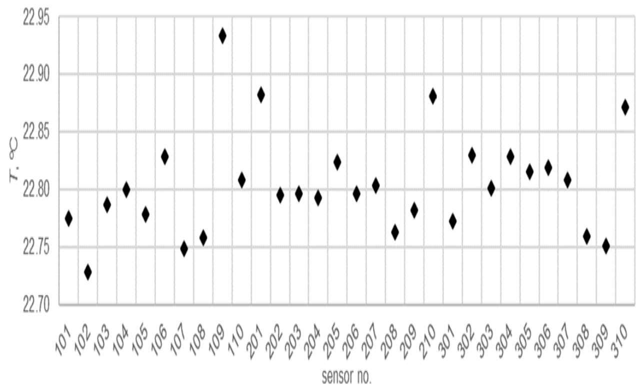

Fig. 3. Measurements results for all the calibrated Pt100 temperature sensors

As presented in Table 1, the calculated corrections have significant value in relation to the resolution of the temperature measurements.

The above-mentioned calibration procedure was repeated twice, 3 and 6 months after the initial calibration. The exemplary results are presented in Table 2. The highest difference was reported for sensor no. 301 between first and second calibration, where the differences between corrections was 0.006°C. On the other hand, the differences were not noticeable in second and third calibration for all of the sensors. Thus, it may be assumed, that the calibration process could be repeated not more often that every 3 months.

Table 2 The selected corrections for each sensor for different times after the initial calibration

Lp.	Time after initial calibration, days	Sensor No.	103	108	205	301	307
1	0	ΔT, °C	-0.010	-0.038	0.027	-0.025	0.011
2	110		-0.010	-0.038	0.028	-0.019	0.014
3	220		-0.010	-0.038	0.028	-0.019	0.014

Temperature distribution measurements

Measurement setup

The developed multipoint temperature sensing system was then used to characterise the thermostatic chamber properties. The temperature distribution was measured using 27 temperature sensors arranged according to the diagram shown in Figure 4. The chamber was divided into 3 vertical sections: A, B, and C while each section contained 9 temperature measurement locations.

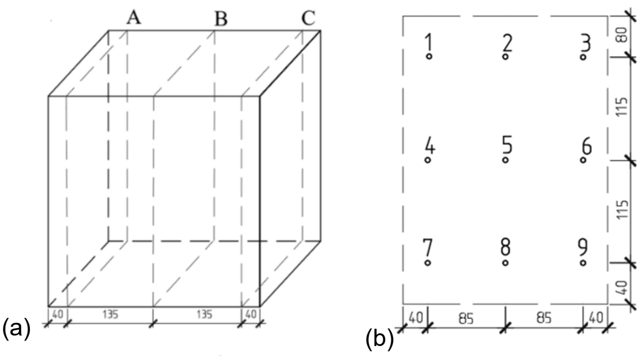

Fig. 4. Arrangement of the temperature measurement locations in the thermostatic chamber (dimensions in mm): (a) arrangement of the vertical sections, (b) arrangement of the measurement locations in the sections

Results

Table 3 presents the summary of the temperature gradient measurements.

Table 3 Results of temperature gradient measurements

Fan setting	T_{max}, °C	T_{min}, °C	$(T_{max}-T_{min})$, °C	$(T_{2max}-T_{2min})$*, °C
off	22.700	22.494	0.207	0.102
full speed	22.764	22.462	0.302	0.219

*only sensors 1-6 (see Fig. 4b)

When the fan is turned off the maximum temperature difference between any given point inside the chamber is close to 0.2°C while when the fan is set to full power it increases up to 0.3°C. However, if the sensors 7-9 (see Fig.4b), located in the lower area of the chamber, are not taken into consideration, the maximum temperature difference decreases by about 0.1°C.

The results obtained for temperature distribution for all the Pt100 sensors are presented in Fig. 5-6 in which the difference between the temperature registered by each i-th sensor T_i and the temperature recorded by the sensor 203 T_{203} located in the middle of the chamber (point B5) is shown.

Fig. 5 presents the measurement results obtained when the fan was turned off and therefore the registered temperature gradient shows a noticeable convective nature. The temperature gradient in the middle area of the chamber (sensors 4-6 - see Fig.4b) is below -0,02°C. On the other hand, Fig. 6 illustrates the results obtained when the fan speed was set to 'full speed' and in this case the temperature gradient is different from that presented earlier in Fig. 5. In this case, the increased cooling is observed in area A, that is caused by the fan, which is placed above the sensor A3 (see Fig 4.).

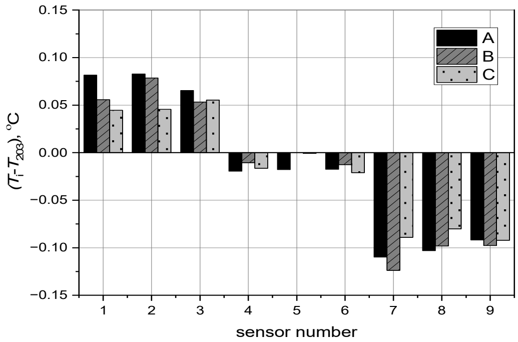

Fig. 5. Temperature distribution for all sensors in sections A, B and C (conditions: set temperature T_u= 23°C, fan setting 'off')

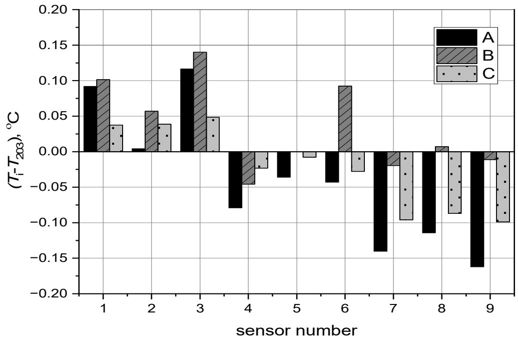

Fig. 6. Temperature distribution for all sensors in sections A, B and C (conditions: set temperature T_u = 23°C, fan setting 'full speed`)

Temperature stability measurements

The temperature stability was analysed in long-term period for 70 h (3 days). The results are presented in Fig. 7. The temperature stabilizes to ±0.005°C in approximately 3.3 h. As shown in Fig. 7. some long-term oscillations with period of 24-27 h are observed which may be related to slight ambient temperature variations.

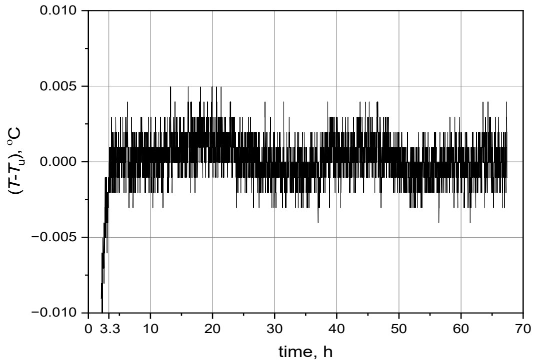

Fig. 7. Temperature stability in time, (conditions: sensor 203 placed in the middle of the chamber (point B5), the set temperature T_u = 23°C, fan set to 'off')

The stabilization process properties, such as the overshoot ΔA, and the regulation t_r time, when the temperature oscillations fall below ±0.01°C threshold were examined for the extreme set temperatures 21.0°C and 25.5°C. The corresponding results are presented in Table 4.

Table 4 Results of temperature stability measurements

T_u, °C	Fan setting	t_r, h	Δ*A*, %
21.0	off	2.24	0.31
	half speed	1.97	0.23
	full speed	1.86	0.25
25.5	off	1.23	0.07
	half speed	1.10	0.10
	full speed	1.00	0.17

If the fan is turn on the regulation time t_r decrease. The overshoot is higher when temperature inside the chamber is lower than the outside temperature and the cooling of the chamber interior is needed.

The exemplary temperature-time dependence registered in the following conditions: the set temperature T_u = 21°C, and the fan turned off is presented in Fig. 8.

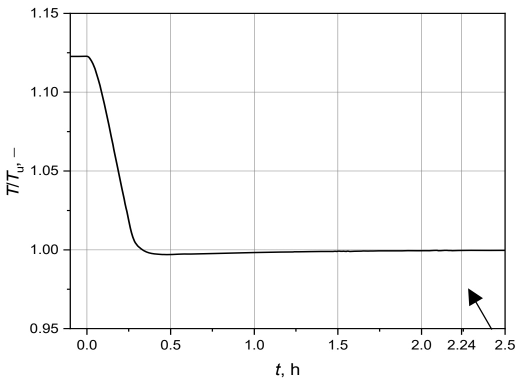

Fig. 8. The exemplary temperature stabilisation curve, the time t_r = 2.24 is pointed (conditions: the set temperature T_u = 21°C, fan set to ‘off’, results for sensor 203 placed in the middle of the chamber – point B5)

Conclusions

The described temperature measurement system allows for precise measurements of the temperature gradient and stability inside a thermostatic chamber. Relatively long time between calibrations enables easy and convenient use of the system. The capability to record a large number of measurement data in real time enables determination of the temperature gradient in the chamber as well as the identification of disturbances and the analysis of their impact on the chamber's temperature. The presented results of temperature gradient measurements are similar to the previous measurements which were obtained using a single thermometer system [2]. The developed system can be straightforwardly utilized for commercial purposes as well as in research engagements in case of thermostatic chambers of various designs and volumes.

Although the described chamber is of low-cost design, it provides remarkably good thermal properties. It allows to maintain the temperature with a stability of at least ±0.01 °C (while in some cases even ±0.005 °C can be obtained). The maximum gradient of the temperature in the chamber volume is better than 0.2 °C (if the fan is turned off) which is also an acceptable value.

Furthermore, the new, user friendly LCD based interface also proved to be very convenient. Ability to quickly check thermostatic chamber status, change the setpoint and observe temperature trend in time is very useful.

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