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The analysis of the metrological properties of contact temperature measurement with the use of selected statistical methods

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Abstract—**In this study, the uncertainty of measurement paths was estimated using selected statistical methods. Specifically, temperature measurements obtained from contact temperature sensors used in a heat transfer test section were investigated. The experiments utilized a dry-well temperature calibrator, thermoelements (types K, J, N, and T), and a data acquisition station. Additionally, a certified Pt-100 resistance sensor connected to the temperature meter was considered during measurements. The temperature range for the selected measurement points was 0.3 to 100 °C, covering both increasing and decreasing temperatures. To calculate the expanded uncertainty, both the uncertainty propagation method and the Monte Carlo method were employed. The results were analyzed and found to be similar.**

Keywords—**Temperature measurement; thermoelements; calibration; measurement uncertainty; Monte Carlo method; statistical methods**

I. Introduction

TEMPERATURE measurement is crucial in experiments focused on heat transfer. Research on boiling heat transfer during refrigerant flow in minichannels has been carried out at Kielce University of Technology for many years [1]–[5]. Key topics in experiments are measurements of fluid temperature realized at the channel inlet and outlet of a model mini heat exchanger. K-type thermoelements were used for fluid temperature measurement. Furthermore, temperature measurements of the heated wall were made with the use of contact [1]–[4] or contactless methods [4], [5].

In the literature, each publication that presents experimental results should include error analysis, mainly based on measurement quantity uncertainties, comprising individual components and a measurement path. The calibration procedure for the individual components of the measurement test section is presented, for example, in [6]–[9], where the authors focus on the use of contact sensors for temperature measurement. The calibration procedure for the NTC thermistor was described in [6]. In [7] the calibration procedure for a K-type thermoelement was discussed, while in [8], [9] resistance sensors were of the main interest. An experimental evaluation of the uncertainty of a measurement path with an analog-to-digital converter card is described in [10]. It should be emphasized that there is a lack of publications devoted to the calibration of complete measurement paths.

The main aim of this work is to analyze the metrological properties of selected measurement paths equipped with sensors for contact temperature measurement, expressed in terms of uncertainty. The measurement path is an integral part of the experimental rig dedicated to investigations on heat transfer with change of phase (boiling process) of the working fluid flowing in the test section with minichannels. In the platinum thermal resistance Pt-100 sensor (RTD), class A [11], was used as a reference temperature to measure the temperature that prevails at the output of the dry-well calibrator. The calibrator was a heat source to ensure a constant reference temperature. The Pt-100 sensor was connected to an EMT-55 meter [12].

A short literature review is presented to highlight experimental research related to the need for temperature measurement and to emphasize the current necessity for improving measurement precision. The state-of-the-art review focuses on temperature measurement methods and their application in heat exchange systems. It is important to underline that thermoelements of various types differ in terms of measurement ranges and temperature accuracy.

Numerous experiments have been conducted using various types of thermoelements. In [13] the authors analyzed the heat transfer mechanisms concerning vapor qualities and oil concentrations for the R32-oil mixture during flow boiling, based on experimental results. Nine T-type thermoelements were used to determine temperatures during the tests. The thermoelements were placed within a copper tube. In [14] thermoelements were applied to analyze convective boiling heat transfer with the effect of nanoparticle deposition in TiO2-H2O nanofluids within microchannels during flow boiling. Type T thermoelements measured the wall temperatures at the bottom of the microchannel, as well as the working fluid at the inlet and outlet. In [15], the authors used two types of thermoelements: T and N. The former were inserted into the test section at the inlet and outlet to measure fluid temperatures, while the latter measured walls. The authors dealt with flow

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boiling of HFE-7100 in a vertical rectangular minichannel from the onset of boiling to dry-out. The sensitivity of two techniques of biphilic surface coating on boiling and dry-out was examined. For the experiment described in [16], a large nickel plate was used as the test sample, heated to 850 °C before being cooled by a single circular water jet. N- type thermoelements were inserted through the bottom surface. In [17], temperature measurements due to three types of thermoelements (N, T, and K) helped to analyze the effect of condenser tube inclination in a passive containment cooling system for nuclear safety. Temperature measurement due to type K thermoelements, conducted in experiments, was described in [15], [18], [19], while type J thermoelements were applied in the study reported in [20], [19].

In summary, the objective of the following article is to verify which of the newly acquired thermoelements at the Kielce University of Technology will be best suited for temperature measurements during flow boiling experiments involving low-boiling-point liquids (boiling point do not exceed 100°C at normal pressure).

II. Experimental stand and methodology

A view of the test rig is shown in Figure 1.

Fig. 1. View of the test rig: 1 - temperature dry-well calibrator, model CDT-9100-ZERO (WIKA), 2 - meter, model EMT-55 (Czaki Thermo-Product), 3 - data acquisition station, model IOTech DaqLab/2005 (IOtech)

The essential elements of the experimental rig are seven thermoelements, connected to the IOTech DaqLab/2005 data acquisition station (IOtech). In the experiments, a platinum thermal resistance Pt-100 (RTD) sensor, class A, was used as a reference temperature to measure the temperature that prevails at the output of the temperature dry-well calibrator. The Pt-100 sensor was connected to an EMT-55 meter [12].

Several temperature sensors were calibrated at temperatures corresponding to normal boiling points of liquids, used as working fluids in previously conducted heat transfer experiments, and at 0 °C. Six refrigerants, manufactured by 3M [21], have been used in the research, that is, HFE-7000, HFE-649, FC-72, HFE-7100, HFE -7200 and FC-770. Two other liquids were ethanol and demineralized water. The temperatures corresponding to the normal boiling points of the liquids listed above (at a pressure of 101 325 Pa) are: 34 °C, 49 °C, 56 °C, 61 ° C, 76 ° C, 78 °C [22], 95 °C, and 100 °C [23], respectively. The dry-well temperature calibrator model CDT-9100-ZERO (WIKA) was used as a heat source to ensure a constant reference temperature. The temperature range of this calibrator is between 0 °C and 100 °C, while the highest nominal accuracy is guaranteed at 0 °C [24].

In the first stage of the experimental series, the selected thermoelements were placed in the dry-well calibrator (at maximum depth), as recommended in [25]. There were two thermoelements of three types, as follows: K, J, N, and one T- type thermoelement, all manufactured by Czaki Thermo-Product (Raszyn-Rybie, Poland). The basic data of all thermoelements selected for testing are listed in Table I. The nominal accuracy of the thermoelements is indicated according to the valid applicable standards [26], while the nominal measurement range results from information provided by the manufacturer of these temperature sensors [27].

TABLE I
CHARACTERISTIC OF THE TESTED THERMOELEMENTS

No.	Type /Designation	Accuracy	Measurement range		L	ϕ
			From	To		
		°C	°C	°C	mm	mm
1.	T/TT	0.5 or 0.004·|t|	-40	300	200	0.5
2.	J/TJ-1	1.5 or 0.004·|t|	-40	400	200	0.5
3.	J/TJ-2	1.5 or 0.004·|t|	-40	400	200	0.5
4.	N/T14N-1	1.5 or 0.004·|t|	-40	1000	200	1
5.	N/T14N-2	1.5 or 0.004·|t|	-40	1000	200	1
6.	K/TK-1	1.5 or 0.004·|t|	-40	600	600	0.5
7.	K/TK-2	1.5 or 0.004·|t|	-40	600	600	0.5

where: L - length of a thermoelement, ϕ - diameter of thermoelement sheath, t - temperature of thermoelement measuring junction.

The prevailing temperature in the temperature controlled metal block of the dry-well calibrator [24] was measured with the help of the platinum resistance thermometer Pt-100 class A and an EMT-55 meter, which has the calibration certificate issued by the device manufacturer [28]. This meter was treated as a working standard that provides reference results for temperature measurement. The assumption was made that the uncertainty associated with the measurement of temperature using an RTD sensor is contingent not only on the measured temperature and standard deviation values (type A uncertainty), but also on the error inherent in the signal conditioning circuit [8], a fundamental component of the EMT-55 meter (type B uncertainty). Moreover, during the calibration experiment, the working standard was treated as a single measuring device. All thermoelements under test were equipped with compensation cables connected to the DBK-81 Expansion Card used to condition analogue signals (IOtech) [29], cooperated with the IOTech DaqLab/2005 data acquisition station [30].

The scheme of elements of the experimental rig is shown in Figure 2. The uncertainty values necessary for calculations were assumed in metrological analyzes, with respect to compensation cables, the DBK-81 module, and IOTech DaqLab/2005 data acquisition station, due to the appropriate standards [31] or specific information according to the manufacturer of each device [29], [30], respectively.

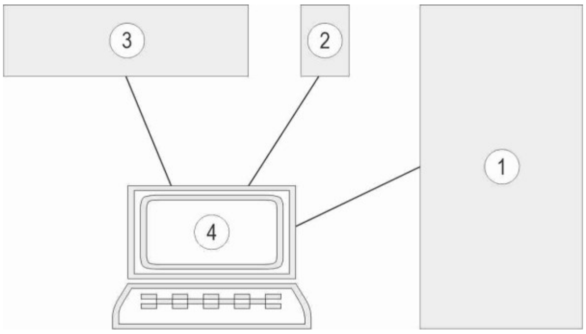

Fig. 2. Scheme of the test rig, showing connections between its main elements, 1 - dry-well temperature calibrator, model CDT-9100-ZERO (WIKA), 2 - temperature meter, model EMT-55 (Czaki Thermo-Product), 3 - data acquisition station, model IOTech DaqLab/2005 (IOtech), 4 – PC.

During the experimental series, each value of the selected temperatures was set due to the dry-well calibrator control system, in the range (approximately) from 0 °C to 100 °C. Ten temperature values of the set temperature, named as t_{kz}, were taken into consideration. These temperatures correspond to the boiling points of the selected fluids under normal conditions. As mentioned above, such fluids were applied in flow boiling heat transfer investigations in minichannels. Additional temperature values resulted from those given in the calibration certificate of the EMT-55 meter [28].

The experiment was carried out under steady conditions. After setting the temperature value t_{kz}, the 30 to 40 minute time interval between temperature sets was assumed to ensure temperature stabilization. To collect the measurement data, DAQView software was applied, which cooperated with the IOTech DaqLab/2005 data acquisition station.

For each temperature, the measurement data were recorded every 1 s, with a full measurement series lasting 300 seconds. The number of measurements in each series was chosen based on the experience of the authors and the analysis conducted in [10]. The first part of the experimental series with increasing temperature ended at a temperature of 100 °C. To check whether there is hysteresis in the temperature readings, a second part of the experiment was carried out, in which the temperature was reduced in the range from 100 °C to that 0 °C, analogous to the set in the first part of the experiment. The selected temperatures for the measurements were as follows: 95.1 °C; 78.4 °C; 76.1 °C; 61 °C; 56.1 °C; 49.2 °C; 34.2 °C; 20.1 °C and 0.3 °C. In the second part of the experiment, the time interval between the setting values of t_{kz} was assumed to be at least 40 minutes to achieve stabilization of the temperature.

The experiment proceeded analogously to its first part. It should be explained that the difference in the time interval for temperature stabilization was due to the different ‘heating’ and ‘cooling’ time intervals (corresponding to increasing and decreasing temperature, respectively), known from the temperature calibrator data sheet, delivered by the dry-well temperature calibrator (WIKA CDT-9100-ZERO). The Pt-100 sensor was located together with other thermoelements in the temperature dry-well of this calibrator, throughout the experimental series. The connection of the RTD sensor to the EMT-55 meter was provided by means of a shielded four-wire line with a length of 2 000 mm, similar to [6], to eliminate the influence of wire resistance on the accuracy of the temperature measurement [32].

The resistance value of the platinum thermometer was automatically converted to a temperature reading on the EMT-55 meter. The class A resistance sensor used in the experiment is characterized, according to the standard [33], by a temperature measurement accuracy of ± (0.15 + 0.002 | t |) in a temperature range of -100° C to 450° C. The physical parameters of the ambient air in the laboratory room were as follows: ambient temperature of 26.7 °C; relative humidity of 26 % RH and atmospheric pressure of 99 820 Pa.

III. EXPERIMENTAL RESULTS

Table II shows the deviations based on the temperatures measured by the thermoelements that were analyzed.

TABLE II

DEVIATIONS OF THE COMPARED THERMOELEMENTS

Designation	T, °C	Deviation from Pt-100, °C	Deviation from t_{iz}, °C
$t_{1z} = 0.3$ °C ↑			
Pt-100	0.3	–	0
TT, TJ-2	0.3 ± 0.1	0.0 ± 0.1	0.0 ± 0.1
TJ-1	$0.3^{+0.1}_{-0.2}$	$0.0^{+0.1}_{-0.2}$	$0.0^{+0.1}_{-0.2}$
TK-1	0.5 ± 0.2	0.2 ± 0.2	0.2 ± 0.2
TK-2*	0.1 ± 0.2	0.2 ± 0.2	0.2 ± 0.2
TK-2^	0.1 ± 0.2	$0.0^{+0.2}_{-0.1}$	$0.0^{+0.2}_{-0.1}$
TN14-1	-0.3 ± 0.2	-0.6 ± 0.2	-0.6 ± 0.2
TN14-2	-0.4 ± 0.2	-0.7 ± 0.2	-0.7 ± 0.2
$t_{5z} = 56.1$ °C ↑			
Pt-100	55.9	–	-0.2
TT	55.5 ± 0.1	-0.4 ± 0.1	-0.6 ± 0.1
TJ-2	56.0 ± 0.1	-0.2 ± 0.1	0.1 ± 0.1
TJ-1	$56.1^{+0.1}_{-0.2}$	$-0.1^{+0.1}_{-0.2}$	$\pm 0.1^{+0.1}_{-0.2}°C$
TK-1	55.4 ± 0.2	0.5 ± 0.2	0.7 ± 0.2
TK-2	$55.6^{+0.2}_{-0.1}$	$-0.3^{+0.2}_{-0.1}$	$-0.5^{+0.2}_{-0.1}$
TN14-1	$55.4^{+0.2}_{-0.3}$	$-0.4^{+0.2}_{-0.3}$	$-0.6^{+0.2}_{-0.3}$
TN14-2	55.5 ± 0.3	-0.4 ± 0.3	-0.6 ± 0.3
$t_{10z} = 100$ °C			
Pt-100	100.5	–	– 0.5
TT	100.2 ± 0.1	$-0.3^{+0.1}_{-0.3}$	$0.2^{+0.1}_{-0.3}$
TJ-2	100.2 ± 0.2	-0.3 ± 0.2	0.2 ± 0.2
TJ-1	$100.2^{+0.1}_{-0.3}$	$-0.3^{+0.1}_{-0.3}$	$0.2^{+0.1}_{-0.3}$
TK-1&	100.4 ± 0.1	-0.1 ± 0.1	0.4 ± 0.1
TK-1**	100.5 ± 0.1	0.0 ± 0.1	0.5 ± 0.1
TK-2&	99.9 ± 0.2	-0.6 ± 0.2	-0.1 ± 0.2
TK-2**	100.0 ± 0.2	0.5 ± 0.2	0.0 ± 0.2
TN14-1	99.5 ± 0.2	$0.9^{+0.2}_{-0.3}$	$0.4^{+0.2}_{-0.3}$
TN14-2	99.5 ± 0.2	1.0 ± 0.2	0.5 ± 0.2
$t_{5z} = 56.1$ °C ↓			
Pt-100	56.0	–	– 0.1
TT	55.5 ± 0.1	-0.5 ± 0.1	-0.6 ± 0.1
TJ-2	56.1 ± 0.1	0.1 ± 0.1	0.0 ± 0.1
TJ-1	56.0 ± 0.2	0.0 ± 0.1	0.1 ± 0.2
TK-1	55.4 ± 0.2	0.6 ± 0.2	0.7 ± 0.2
TK-2	$55.6^{+0.2}_{-0.1}$	$-0.3^{+0.2}_{-0.1}$	$-0.5^{+0.2}_{-0.1}$
TN14-1, TN14-2	$55.4^{+0.2}_{-0.3}$	$-0.4^{+0.2}_{-0.3}$	$-0.6^{+0.2}_{-0.3}$
$t_{1z} = 0.3$ °C ↓			
Pt-100	0.5	–	– 0.2
TT	0.2 ± 0.1	0.3 ± 0.1	0.1 ± 0.1
TJ-2	0.2 ± 0.2	0.3 ± 0.2	0.1 ± 0.2
TJ-1	$0.2^{+0.1}_{-0.2}$	$0.3^{+0.1}_{-0.2}$	$0.1^{+0.1}_{-0.2}$
TK-1	0.5 ± 0.2	0.0 ± 0.2	-0.2 ± 0.2
TK-2&	-0.1 ± 0.1	0.6 ± 0.1	0.4 ± 0.1
TK-2**	0.0 ± 0.1	0.5 ± 0.1	0.3 ± 0.1
TN14-1	-0.4 ± 0.2	-0.9 ± 0.2	-0.7 ± 0.2
TN14-2	-0.5 ± 0.2	-1.0 ± 0.2	-0.8 ± 0.2

* for the first 240 s of the measurement time interval, ^ from 240 s to 300 s of the measurement time interval; & for the first 60 s of the measurement time interval; **from 60 s to 300 s of the measurement time interval; ↑ increasing temperature; ↓ decreasing temperature

Figure 3 illustrates the temperature values, captured by the thermoelements under test and the measurement temperature standard (RTD Pt-100), while each temperature was set in the dry-well temperature calibrator. It should be noted that the temperature correction resulting from the calibration certificate [28] has not been taken into account.

From all temperature values set at the temperature dry-well calibrator, the following were selected to investigate: $t_{1z} = 0.3$ °C, $t_{5z} = 56.1$ °C and $t_{10z} = 100$ °C. Thermoelement of types: K (two items), J (two items), N (two items) and T, were selected for analysis.

When analyzing the results shown in Figure 3 and Table II it can be seen that the type N thermoelements, compared to the other thermoelements tested, showed larger deviations from the reference temperature and the set temperatures. Therefore, while type N thermoelements performed adequately, type J thermoelements, i.e., TJ-2 and TJ-1, showed the closest temperatures to the reference temperature and the set temperatures, with the smallest deviations, making them the most accurate in this context. The type T thermoelement also showed relatively small deviations from the reference temperature and the set temperatures. Furthermore, the type K thermoelements showed larger deviations from the reference temperature and the set temperatures compared to the type T and type J thermoelements. Therefore, the type N thermoelements were not the most accurate in this analysis.

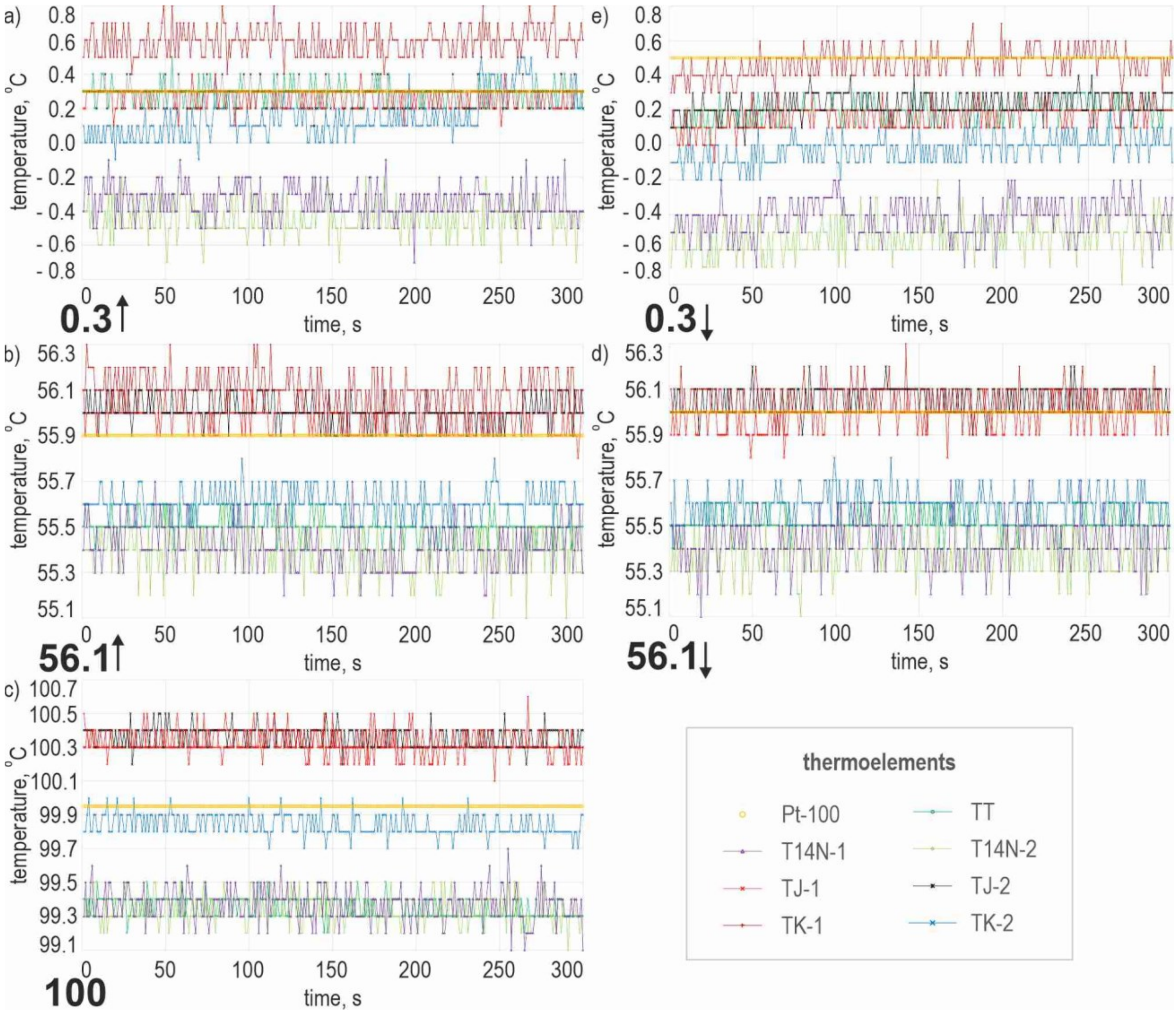

Fig. 3. The temperature values recorded by selected thermoelements, while the temperature in the dry-well temperature calibrator was set as: a) $t_{1z} = 0.3$ °C ↑, b) $t_{5z} = 56.1$ °C ↑, c) $t_{10z} = 100$ °C, d) $t_{5z} = 56.1$ °C ↓, e) $t_{1z} = 0.3$ °C ↓.

IV. Estimation of Measurement Uncertainty

An estimation of measurement uncertainty was carried out considering the working standard and the reference temperature source due to the temperature dry-well calibrator. The type A standard uncertainty of the temperature measurements was determined for all measurement paths. A type B standard uncertainty was estimated for the IOTech DaqLab/2005 data acquisition station with DBK-81 Expansion Card and measurement paths. An expanded standard uncertainty was calculated for the individual measurement paths. Furthermore, the Monte Carlo method was used to estimate the uncertainties listed above.

A. Estimation of measurement uncertainty of the dry-well temperature calibrator

The temperature t_{iref} at the output of the dry- well temperature calibrator, while the in-built thermometer indicates k- th temperature equals t_{kz}, is based on the measurement of the working standard, placed in the temperature controlled metal block of the calibrator (RTD Pt-100, class A and the EMT-55 meter). The temperature t_{iref} is calculated from the following relationship:

$$t_{iref} = t_{kz} + \delta t_a + \delta t_v + \delta t_r + \delta t_A + \delta t_R + \delta t_D \qquad (1)$$

where: t_{iref} - the *i-th* temperature measured by the working standard, t_{kz} - the *k-th* temperature set at the input of the temperature dry-well calibrator, δt_a - the accuracy error of the temperature calibrator, defined as the discrepancy between the measured value and the reference value [24], as derived from the manufacturer's documentation, is 0 ± 0.05 °C for 0 °C and 0 ± 0.1 °C for other temperatures; δt_v - the temperature stability error, which is the maximum temperature difference at a stable temperature achieved during time interval of 30 minutes, estimated as 0 ± 0.05 °C, based on the manufacturer's documentation [24]; δt_r - the temperature calibrator setting resolution for the built-in dry-well temperature calibrator thermometer, assumed as 0.1 °C [24]; δt_A - the error related to the axial gradient of the temperature, which takes into account the temperature variation in the metal block of the dry- well calibrator, assumed as 0 ± 0.05 °C, based on the manufacturer's documentation [24]; δt_R - the error related to the temperature difference in the radial direction in the metal block of the dry-well calibrator (between the built- in thermometer and the working standard), estimated as 0 ± 0.10 °C; δt_D - the error resulting from the potential change in the indication of the temperature value of the working standard since its last calibration, caused by the ageing of the material of the resistive sensor, estimated as 0 ± 0.02 °C, on the basis on the known properties of RTD sensors of the Pt-100 type [32].

Table III presents the uncertainty budget for the WIKA CDT -9100-ZERO temperature calibrator.

TABLE III
UNCERTAINTY BUDGET t_{iref} OF THE WIKA CDT-9100-ZERO DRY-WELL TEMPERATURE CALIBRATOR

Quantites	Estimates	Standard uncertainty	Probability distribution	Sensitivity coefficient	Contribution of uncertainty
X_i	x_i	$u(x_i)$		c_i	$u_i(y)$
	°C	°C			°C
t_{1z}	0.3	0.10 [28]	normal	1.0	0.1
t_{2z}	20.1	0.10 [28]	normal	1.0	0.1
t_{3z}	34.2	0.10 [28]	normal	1.0	0.1
t_{5z}	56.1	0.10 [28]	normal	1.0	0.1
t_{8z}	78.4	0.10 [28]	normal	1.0	0.1
t_{10z}	100	0.10 [28]	normal	1.0	0.1
δt_a^{*}	0.0	0.029 [24]	rectangular	1.0	0.029
δt_a^{**}	0.0	0.058 [24]	rectangular	1.0	0.058
δt_v	0.0	0.029 [24]	rectangular	1.0	0.029
δt_r	0.0	0.029 [24]	rectangular	1.0	0.029
δt_A	0.0	0.029 [24]	rectangular	1.0	0.029
δt_R	0.0	0.058 [24]	rectangular	1.0	0.058
δt_D	0.0	0.006 [28]	rectangular	1.0	0.006

*for 0°C, **for other temperatures set on the dry-well temperature calibrator.

Table III omits the temperature error due to heat conduction through the sheath of the thermometer, because the diameter of the thermoelements tested was significantly less than 5 mm [32]. The following types of probability distributions specified in Table III were assumed: rectangular - based on the equipment manufacturer's documentation [32] and normal - based on the information contained in the calibration certificate [28], particularly with respect to the calibration method.

Since the quantities involved in formula (1) are independent, the combined standard uncertainty, calculated according to the aw of propagation of uncertainty (described in the literature [34], which involves folding standard deviations of uncorrelated errors), can be expressed as follows:

$$u(t_{iref}) = \sqrt{u(t_a)^2 + u(t_v)^2 + u(t_r)^2 + u(t_A)^2 + u(t_R)^2 + u(t_D)^2} \qquad (2)$$

where $u(t_{iref}) = 0.096$ °C for 0°C, and $u(t_{iref}) = 0.108$ °C for other temperatures. The uncertainty components considered in formula (2), obtained by assuming specific probability distributions for independent errors, contribute comparably to the uncertainty of the standard output estimate and exceed three in number. Consequently, the conditions stipulated by the central limit theorem [32] are satisfied, which allows the assumption, with a high level of approximation, that the distribution of the output quantity follows a normal distribution. Therefore, for a normal distribution and a probability distribution assumed to be 0.95, the standard coverage factor $k = 2$ was used.

For the assumed coverage factor, the expanded uncertainty value was $U(t_{iref}) = 0.19$ °C for 0°C and $U(t_{iref}) = 0.21$ °C for the remaining temperatures. According to the calibration certificate [28], the standard uncertainty of the EMT-55 measuring instrument fitted with the resistance sensor Pt-100 class A is $u(t_{EMT}) = \pm 0.1$ °C. The manufacturer's documentation [29] specifies an error in the IOTech DaqLab/2005 data acquisition station together with the card DBK-81, as $\delta t_{DAS} = \pm 0.8$ °C.

B. Estimation of type A standard uncertainty for the measurement paths

The uncertainties of temperature measurements were estimated for thermoelements, the characteristics of which are shown in Table I. The thermoelements were placed in the WIKA CDT-9100-ZERO dry-well temperature calibrator during the calibration experiment. Estimates of the mean errors were determined, which are the squares of the differences between the temperature measurements of the tested thermoelements and the temperature recorded with the reference thermometer with the Pt-100 sensor.

The type A measurement uncertainty was estimated for all test paths according to the following equation [32]:

$$u_A(t_j) = \sqrt{\frac{\sum_{i=1}^{n}\left(t_{ijx} - \overline{t_{EMT}}\right)^2}{(n-1)}} \qquad (3)$$

where: t_{ijx} – the *i-th* temperature measurement recorded by the *j-th* thermoelement, $\overline{t_{EMT}}$ – the arithmetic mean of temperatures from the series of temperature measurements collected by the reference thermoelement, reduced by the value of the corrective adjustment defined in the calibration certificate [28]; n – the number of measurements in the experimental series. The results are presented in Table IV.

TABLE IV
AVERAGE AND TYPE A STANDARD UNCERTAINTY $u_A(t_j)$ FOR THE MEASUREMENT PATHS

k	t_{kz}	Thermoelement													
		TT		TJ-1		TJ-2		T14N-1		T14N-2		TK-1		TK-2	
		$\overline{t_{jx}}$	$u_A(t_j)$	$\overline{t_{jx}}$	$u_A(t_j)$	$\overline{t_{jx}}$	$u_A(t_j)$	$\overline{t_{jx}}$	$u_A(t_j)$	$\overline{t_{jx}}$	$u_A(t_j)$	$\overline{t_{jx}}$	$u_A(t_j)$	$\overline{t_{jx}}$	$u_A(t_j)$
-	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
1	0.3↑	0.29	0.06	0.26	0.05	0.28	0.08	-0.34	0.61	-0.45	0.71	0.59	0.27	0.16	0.20
1	0.3↓	0.19	0.28	0.16	0.31	0.24	0.31	-0.42	0.88	-0.52	0.99	0.47	0.10	-0.02	0.49
2	20.1↑	19.78	0.26	19.90	0.15	19.95	0.10	19.57	0.48	19.48	0.56	20.16	0.30	19.66	0.38
2	20.1↓	19.74	0.44	19.87	0.31	19.97	0.08	19.56	0.63	19.49	0.69	20.03	0.07	19.60	0.59
3	34.2↑	33.75	0.55	34.02	0.29	34.06	0.13	33.67	0.64	33.61	0.69	34.26	0.20	33.76	0.58
3	34.2↓	33.71	0.55	33.97	0.29	34.06	0.13	33.62	0.64	33.56	0.69	34.13	0.20	33.97	0.58
5	56.1↑	55.51	0.40	55.97	0.09	56.01	0.12	55.42	0.49	55.38	0.53	56.10	0.22	55.61	0.30
5	56.1↓	55.51	0.49	55.98	0.06	56.05	0.08	55.42	0.58	55.37	0.64	55.05	0.08	55.59	0.41
8	78.4↑	77.76	0.51	78.47	0.21	78.52	0.40	77.72	0.56	77.67	0.61	78.54	0.41	78.00	0.27
8	78.4↓	77.69	0.68	78.41	0.08	78.48	0.26	77.68	0.69	77.61	0.77	78.43	0.22	77.92	0.46
10	100	99.35	0.64	100.31	0.32	100.36	0.46	99.37	0.63	99.34	0.66	100.34	0.44	99.84	0.16

where: measurements at ↑ - increasing and ↓ - decreasing temperature, $\overline{t_{jx}}$ – arithmetic mean of the temperatures from the series of measurements collected by the *j-th* thermoelement

C. *Estimation of the uncertainty for the measurement paths*

The uncertainty of the temperature measured by the thermoelements under test was determined as follows:

$$t_{jx} = t_{iref} + \delta t_{iref} + \delta t_{jT} + \delta t_s + \delta t_{jK} + \delta t_{DAS} + \delta t_r + \delta t_D \quad (4)$$

where: t_{jx} - the temperature measured by the j-th thermoelement, t_{iref} – i-th the temperature prevailing in the measuring bore of the temperature calibrator, described by equation (1); δt_{iref} - the measurement error of the temperature prevailing in the measuring bore of the temperature calibrator; assuming $\delta t_{iref} = 2 \cdot u(t_{iref})$, $u(t_{iref})$ calculated in accordance with model (2), its value equals 0 ± 0.192 °C for 0 °C and 0 ± 0.216 °C for the remaining temperatures; δt_{jT} – the temperature measurement error of j-th thermoelement read from the standard [26] amounts to 0 ± 1.50 °C for thermoelements type: K, J, N, and 0 ± 0.50 °C for thermoelement type T; δt_s – the error of stability of the temperature of the data acquisition station during the measurement, read based on the alterations in the indications of temperature on the dedicated channel of the station, equals 0±0.10 °C; δt_{jK} – the temperature measurement error for j-th compensating cable, according to the standard [31], its value equals 0 ± 1.50 °C for compensating cables type: K, J, N, and 0 ± 0.50 °C for cables type T; δt_{DAS} – the error related to the accuracy of the temperature measurement using the IOtech DaqLab 2005 data acquisition station linked with the DBK-81 card, assumed in accordance with the manufacturer's documentation [29] as 0 ± 0.80 °C; δt_r – the temperature measurement error related to the thermoelement resolution [30] equals 0.1 °C; δt_d – the error in the temperature measurement caused by the ageing of the data acquisition station, based on the manufacturer's documentation [30], estimated as equal to 0.02 °C.

Table V summarizes the data that constitute the uncertainty budget of the tested measurement paths. It should be explained that the process of selecting probability distributions was identical to the procedure used for the distributions presented in Table III.

By applying the rule of compositing standard deviations of non-correlated errors, as per EA-4/02 M:2022, a type B standard deviation $u_B(t_{jx})$ was calculated for the tested measurement paths:

$$u_B(t_{jx}) = \sqrt{u(t_{iref})^2 + u(t_{jT})^2 + u(t_s)^2 + u(t_{jK})^2 + u(t_{DAS})^2 + u(t_r)^2 + u(t_d)^2} \quad (5)$$

The combined standard uncertainty, denoted as $u(t_{jx})$, of the measurement paths assumes the following form as per reference [6]:

$$u(t_{jx}) = \sqrt{u_A(t_j)^2 + u_B(t_{jx})^2} \quad (6)$$

The calculated type B standard uncertainty values for the test paths $U(t_{jx})$, are as follows: ±0.63 °C for paths fitted with the T-type thermoelement and ±1.33 °C for paths fitted with other types of thermoelements. The calculated standard uncertainty values $u(t_{jx})$, are presented in Table VI.

Table VII displays the values of extended uncertainty, $U(t_{jx})$, computed under the assumption that the probability distribution of the temperature measured by the *j-th* thermoelement of the measurement path follows a normal distribution at a coverage probability of 0.95. Thus, in accordance with [32], the coverage factor is equal to 2.

TABLE V
UNCERTAINTY BUDGET OF THE ANALYZED MEASUREMENT PATHS.

Quantites	Estimates	Standard uncertainty	Probability distribution	Sensitivity coefficient	Contribution of uncertainty
X_i	x_i	$u(x_i)$		c_i	$u_i(y)$
$\delta t_{ref}{}^{*}$	0.0 °C	0.096 °C (2)	normal	1.0	0.096 °C
$\delta t_{ref}{}^{**}$	0.0 °C	0.108 °C (2)	normal	1.0	0.108 °C
$\delta t_{jT}{}^{\wedge}$	0.0 °C	0.877 °C [26]	rectangular	1.0	0.877 °C
$\delta t_{jT}{}^{\wedge\wedge}$	0.0 °C	0.292 °C [26]	rectangular	1.0	0.292 °C
$\delta t_{jK}{}^{\wedge}$	0.0 °C	0.877 °C [29]	rectangular	1.0	0.877 °C
$\delta t_{jK}{}^{\wedge\wedge}$	0.0 °C	0.292 °C [29]	rectangular	1.0	0.292 °C
δt_{DAS}	0.0 °C	0.462 °C [30]	rectangular	1.0	0.462 °C
δt_s	0.0 °C	0.058 °C [31]	rectangular	1.0	0.058 °C
δt_r	0.0 °C	0.029 °C [31]	rectangular	1.0	0.029 °C
δt_d	0.0 °C	0.006 °C [31]	rectangular	1.0	0.006 °C

*for 0 °C, ** for other temperatures, ^ for type: K, J, N, ^^ for type T.

TABLE VI
STANDARD UNCERTAINTY $u(t_{jx})$ FOR THE TEST MEASUREMENT PATHS

k	t_{kz}	Thermoelement						
		TT	TJ-1	TJ-2	T14 N-1	T14 N-2	TK-1	TK-2
		$u(t_{jx})$	$u(t_{jx})$	$u(t_{jx})$	$u(t_{jx})$	$u(t_{jx})$	$u(t_{jx})$	$u(t_{jx})$
-	°C	°C	°C	°C	°C	°C	°C	°C
1	0.3↑	0.63	1.33	1.33	1.46	1.51	1.36	1.34
1	0.3↓	0.63	1.36	1.37	1.59	1.66	1.34	1.42
2	20.1↑	0.69	1.34	1.34	1.41	1.45	1.37	1.39
2	20.1↓	0.77	1.37	1.34	1.47	1.50	1.34	1.45
3	34.2↑	0.73	1.37	1.36	1.41	1.43	1.41	1.38
3	34.2↓	0.84	1.36	1.34	1.48	1.50	1.35	1.45
5	56.1↑	0.75	1.34	1.34	1.42	1.43	1.35	1.36
5	56.1↓	0.80	1.33	1.34	1.45	1.48	1.34	1.39
8	78.4↑	0.82	1.35	1.39	1.45	1.47	1.39	1.36
8	78.4↓	0.93	1.34	1.36	1.50	1.54	1.35	1.41
10	100	0.90	1.37	1.41	1.47	1.48	1.40	1.34

where: measurements at ↑ - increasing and ↓ - decreasing setpoint temperature.

D. Monte Carlo estimation of expanded uncertainty

Estimation of the uncertainty of temperature measurement by the thermoelements tested was also carried out using the Monte Carlo (MC) method. Calculations were carried out in Mathematica, following the recommendations formulated in the Guide [35] using the algorithm described in [4]. The temperature of the output quantity is determined from the following dependence:

$$T_j = t_{jx} + \delta t_T \tag{7}$$

where: t_{jx} - is described by equation (4), δt_T - the measurement error of the temperature measured by the tested thermoelement (it was assumed that $\delta t_T = 2\,u_A(t_{jx})$, while $u_A(t_{jx})$ is determined from equation (3)), j - denotes the thermoelement under test.

For the input quantity δt_T, a normal distribution was assumed, while for the other input quantities the probability distributions are given in Tables III and V. Probability density functions (PDF) of output quantities T_j were determined based on equation (7) and assumed probability distributions. For calculating the empirical cumulative distribution functions (eCDF) F_j of the output quantities, first, the output quantities obtained in the MC simulation were sorted in non-decreasing order T_{jr}, $r = 1,, \dots, M$, while next, the sorted values of output quantities were assigned the cumulative probability in the form of:

$$p_{jr} = \frac{r-\frac{1}{2}}{M}, r = 1, \dots, M \tag{8}$$

where: M - the number of Monte Carlo trials.

Quantiles of 0.025 and 0.975 were calculated for each of the distributions defined by the empirical cumulative distribution functions (eCDF) of the output quantities. These quantiles - with a value of appropriately $F_j^{-1}(0.025)$, $F_j^{-1}(0.975)$) - are the endpoints of confidence intervals at the coverage probability amounting to 0.95. Estimation of the uncertainty of temperature measurements by the Monte Carlo method was carried out for a number of trials M equal to 10^6. The confidence interval for the output was symmetric with respect to t_{kz} (as defined in formula (1)), so only the quantile of order 0.975 minus t_{kz} is given in Table VII in the form:

$$U_{MC}(T_j) = F_j^{-1}(0.975) - t_{kz} \tag{9}$$

Table VII presents the comparison of the calculated value of extended uncertainty $U(t_{jx})$ with the value of $U_{MC}(T_j)$ for the tested measurement paths.

TABLE VII
EXTENDED UNCERTAINTY $U(t_{jx})$ AND $U_{MC}(T_j)$ OF THE MEASUREMENT PATHS

t_{kz}	Thermoelements and its corresponding expanded uncertainty													
	TT		TJ-1		TJ-2		T14N-1		T14N-2		TK-1		TK-2	
	$U(t_{jx})$	$U_{MC}(T_j)$	$U(t_{jx})$	$U_{MC}(T_j)$	$U(t_{jx})$	$U_{MC}(T_j)$	$U(t_{jx})$	$U_{MC}(T_j)$	$U(t_{jx})$	$U_{MC}(T_j)$	$U(t_{jx})$	$U_{MC}(T_j)$	$U(t_{jx})$	$U_{MC}(T_j)$
°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
0.3↑	1.26	1.22	2.66	2.51	2.66	2.57	2.92	2.84	3.02	2.91	2.71	2.63	2.67	2.60
0.3↓	1.38	1.35	2.73	2.56	2.74	2.53	3.19	2.99	3.31	3.25	2.67	2.49	2.84	2.72
20.1↑	1.68	1.30	2.68	2.51	2.67	2.48	2.83	2.68	2.89	2.76	2.73	2.54	2.77	2.59
20.1↓	1.55	1.49	2.74	2.56	2.67	2.53	2.94	2.84	3.00	2.87	2.67	2.55	2.91	2.71
34.2↑	1.46	1.42	2.73	2.53	2.72	2.56	2.81	2.67	2.85	2.65	2.82	2.58	2.75	2.59
34.2↓	1.68	1.62	2.73	2.58	2.68	2.56	2.96	2.85	3.01	2.89	2.69	2.52	2.91	2.73
56.1↑	1.50	1.44	2.67	2.52	2.68	2.55	2.84	2.69	2.87	2.76	2.70	2.54	2.73	2.56
56.1↓	1.61	1.55	2.67	2.55	2.67	2.52	2.91	2.76	2.95	2.81	2.67	2.49	2.79	2.67
78.4↑	1.63	1.57	2.70	2.54	2.78	2.56	2.89	2.77	2.93	2.74	2.79	2.53	2.72	2.58
78.4↓	1.86	1.84	2.67	2.51	2.71	2.56	3.00	2.80	3.08	2.90	2.70	2.56	2.82	2.65
100	1.80	1.74	2.74	2.61	2.81	2.62	2.94	2.80	2.97	2.80	2.80	2.60	2.68	2.50

where: the measurements at ↑ - increased and ↓ - decreased the setpoint temperature.

V. CONCLUSIONS

This work presents the results of the estimate of the uncertainty of the measurement paths using selected statistical methods. The path uncertainties determined relate to temperature measurements made with contact sensors (thermoelements, resistance sensors), carried out on a boiling heat transfer test bench during fluid flow in minichannels (as a compact model heat exchanger with minichannels). The experiments carried out used the WIKA CDT-9100-ZERO dry-well temperature calibrator, thermoelements of types K, J, N, T, and the IOTech DaqLab/2005 data acquisition station. The system was completed with the certified Pt-100 resistance sensor connected to the temperature meter, EMT-55 type, manufactured by Czaki Thermo-Product. The tests were carried out for selected measurement points from 0.3 to 100 °C, with increasing and decreasing temperatures.

The hysteresis phenomenon was observed, particularly evident for the mean temperature values calculated from the recorded data by the T-type thermoelement. The uncertainty propagation method and the Monte Carlo method were used to calculate the expanded uncertainty. The expanded uncertainties determined by both methods gave similar results; for the T-type thermoelement they do not exceed 1.86 °C, and 3.31 °C considering other thermoelements, i.e., thermoelement types: K, N and J. It could be underlined that the difference between the expanded uncertainty values calculated by the Monte Carlo method is affected by the assumed value of the coverage factor 2, which only approximates an expanded uncertainty of 95% for a normal distribution.

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