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Contact temperature measurement using selected thermoelements for studies of heat transfer during fluid flow in minichannels – metrology investigations

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Abstract. This work describes metrology investigations that include uncertainty estimation of contact temperature measurements performed using K- and T-type thermoelements. Temperature measurements were essential in experiments on heat transfer during fluid flow in minichannels. The data acquisition station was used as the main system for collecting temperature data. For metrology investigations of temperature measurement by selected thermoelements, a dry well calibrator was applied. The temperatures measured by the thermoelements were statistically compared using the reference temperature preset on the calibrator. Corrections to the temperature measurement performed by the tested thermoelements were calculated. The relative experimental error and the method accuracy for the thermoelement measurement were determined. The uncertainty of the difference in the temperature measurement for the thermoelements tested with respect to the reference temperature was also provided. The results differed depending on whether the temperature increased or decreased. It confirmed the hysteresis phenomenon.

1 Introduction

The temperature monitoring and control system is an integral part of the installation that cooperates with heat exchangers because it ensures their consistent and reliable operation. Experiments conducted at Kielce University of Technology in Poland focused on heat transfer during fluid flow in minichannels. The results and analyses of the investigations were described in many publications; examples of recent articles are [1-6]. The main objective of the work was to intensify heat transfer during refrigerant flow in a mini heat exchanger with parallel channels set at different angles to the horizontal plane. As the working fluid, different cooling fluids were applied, for instance, FC-72, HFE-649, HFE-7000, HFE-7100, HFE-7200. The mean relative errors of the resultant heat transfer coefficient were determined. The uncertainty of temperature measurements was necessary to estimate the uncertainty of heat transfer coefficients.

Temperature measurement can be realized due to contact and non-contact methods. Selection for a specific temperature measurement can be difficult due to many available measurement devices. On the basis of the short state-of-the-art, it can be assumed that the use of thermoelements for temperature measurement, while the contact measurement method can be done, has many advantages.

Temperature sensors that respond to a change in temperature with a change in the thermoelectric force are widely used by researchers. There are different types of thermoelements with unique characteristics. The most popular are T, E, J, K, N, S, R and B, and for high temperatures, the types G, D and C are revealed. In general, the use of K-type thermoelements for measuring temperature is found in a heat transfer investigation in minichannel heat sinks [7-11]. Furthermore, if researchers are guided by the requirements of small uncertainties in temperature measurement, resistance sensors should be considered a good choice. The RTD (*resistance temperature detector*) has become a very useful device because of its high accuracy. The application of Pt100 resistance sensors for temperature measurement was described in [12-15] while Pt1000 – in [16].

Using a contactless method of temperature measurement is sometimes strongly needed in experiments. Infrared thermography is a comfortable method that involves the detection of infrared radiation emitted by an object. IR cameras can monitor temperature during investigations performed under static or dynamic processes. In the literature, infrared thermography is often declared a well-known and comfortable technique for temperature detection, also in the publications of the authors of this paper (cited above). Other works focused on a similar topic can be mentioned [17-20]. Furthermore, the application of the liquid crystal thermography technique as a contactless method of temperature measurement has been designated as interesting and useful by the authors [21-22].

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This article presents methods for estimating uncertainties in temperature measurements using thermoelements (thermoelements K-type and T-type). The results of statistical analyses based on temperature calibration are described. Contact temperature measurements due to thermoelements were applied in the investigation of heat transfer during fluid flow in minichannels.

2 Experimental stand for heat transfer examination

2.1. Experimental stand

The experimental stand for examination of heat transfer during cooling fluid flow in a group of minichannels is illustrated in Fig. 1. It is described in detail in [1-3].

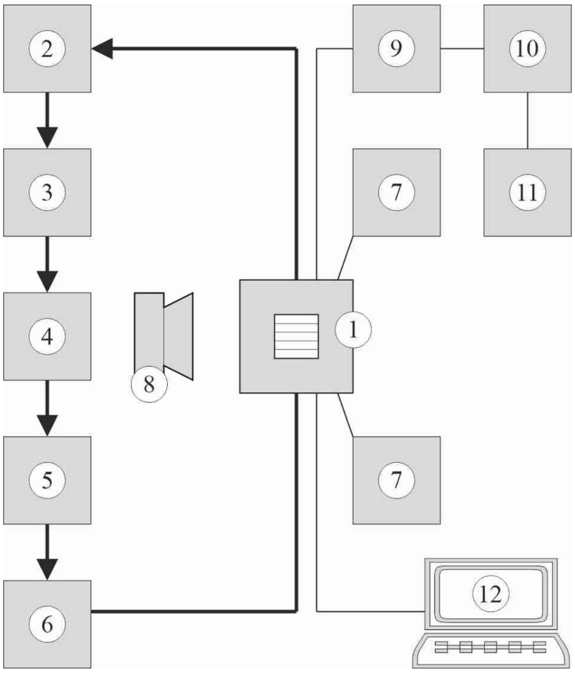

Fig. 1. A schematic diagram of the experimental stand for heat transfer examination: 1 - test section, 2 - heat exchanger, 3 - compensation tank, 4 - filter, 5 - gear pump, 6 - Coriolis mass flow meter, 7 - pressure sensor, 8 - infrared camera, 9 - ammeter, 10 - voltmeter, 11 - power supply system, 12 - data acquisition station cooperating with PC computer.

2.2. Test section

The main part of the experiment stand for heat transfer examination is the test section with parallel rectangular minichannels with a common heated wall. The schematic diagrams of the test section comprising five minichannels are illustrated in Fig. 2. The heated plate was made of Haynes-230 alloy. The outer plate surface temperature was measured by the contactless temperature method, i.e. infrared thermography [1-3,5] or the contact method with the use of thermoelements [4,6]. A flow pattern was observed over the glass on the other side of the heated plate. Pressure meters and thermoelements (K-type) were fitted at the inlet and outlet of the test section.

During the heat transfer experiment, the current supplied to the heated plate is gradually increased. Signals from: thermoelements controlling fluid temperature at the inlet and outlet to the test section, an ammeter and a voltmeter (measured the current intensity or voltage drop across the heater), pressure meters controlled overpressure of the fluid at the minichannel inlet and outlet, an atmospheric pressure gauge and a Coriolis mass flow meter, are recorded by the data acquisition station cooperating with PC computer and appropriate software. On the basis of these data, local heat transfer coefficients are calculated. Additionally, the uncertainty of heat transfer coefficients is estimated. It should be noted that most of the experiments involved subcooled and/or saturated boiling regions.

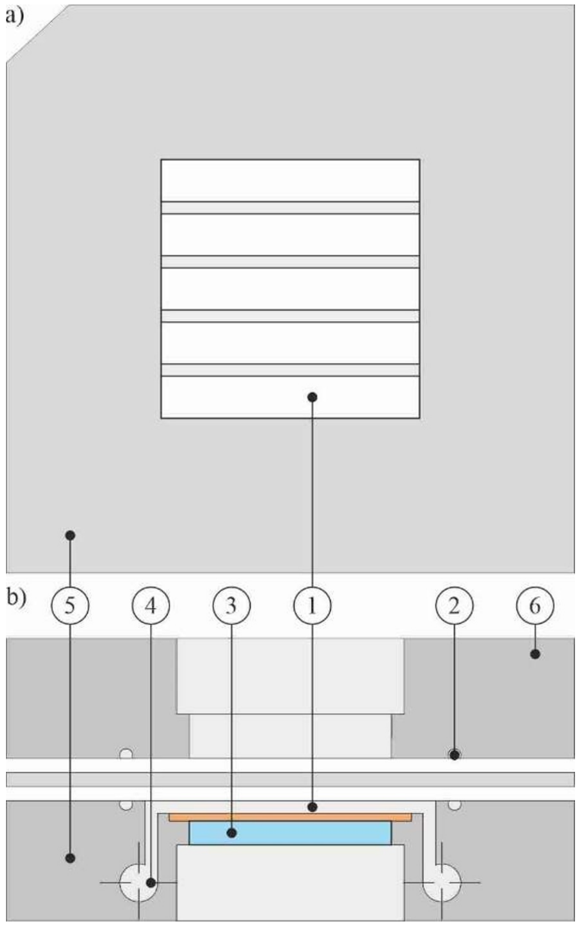

Fig. 2. Schematic diagrams of the test section: a) front view, b) cross-section; 1 - minichannel, 2 - heated plate, 3 - glass plate, 4 - inlet/outlet chamber, 5 - channel body, 6 - front cover.

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3 TEMPERATURE MEASUREMENTS IN METROLOGY INVESTIGATIONS

3.1. Experimental stand

The schematic diagram of the experimental setup for temperature calibration is shown in Fig. 3.

Experimental setup for temperature calibration consists of selected thermoelements (K-type and T-type) with compensation cables, a calibrator, a data acquisition station and a PC computer with appropriate software. In temperature calibration experiments with respect to metrology investigations, a dry well calibrator was applied. It was the CTD9100-ZERO model, manufactured by Wika (Poland).

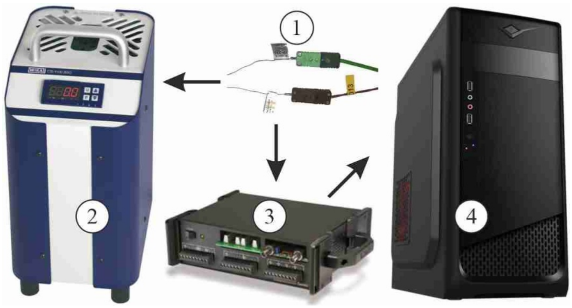

Fig. 3. The schematic diagram of the experimental stand for temperature calibration: 1 - K-type and T-type thermoelements with compensation cables, 2 - dry well calibrator, 3 - data acquisition station, 4 - PC computer with data visualization and an acquisition software.

The main characteristics of the dry well calibrator used in calibration experiments are given in Table 1.

Table 1. Characteristics of the dry well calibrator, model CDT9100-ZERO [23] applied in calibration experiments.

Parameter	Value	Units
Minimum temperature	-10	°C
Reference temperature	0	°C
Maximum temperature	100	°C
Accuracy in 0 °C	0.05	K
Accuracy in remaining range	0.1	K
Stability	< 0.05	K
Resolution	0.1	°C
Axial homogeneity	< 0.05	°C
Temperature control		
Time of heating from −10 °C to 100 °C (minimum)	900	s
Cooling time from 23 °C to 0 °C	300	s
Cooling time from 100 °C to 0 °C	600	s

3.2 Characteristics of thermoelements

For temperature measurement, thermoelements that respond to a change in temperature with a change in the thermoelectric force were applied.

As the first thermoelement, the K-type thermoelement (NiCr-NiAl), the TP-221 model, was tested. It was manufactured by Czaki Thermo-Product (Poland) [24]. This K-type thermoelement had a sheathed sensor with a diameter of 0.5 mm and a length of 600 mm. Its measurement junction was galvanically isolated from the sheath (type b). The accuracy of the temperature measurement due to this thermoelement is 1.5 °C in the range of -40 °C ÷ 600 °C, according to its manufacturer. It also complies with the standard [25].

As the other thermoelement, the T-type (Cu-CuNi) was chosen, manufactured by Guenther (Germany) [26]. It had a sheathed sensor with a diameter of 0.5 mm and a length of 400 mm. Its measurement junction was also galvanically isolated from the sheath. The accuracy of the temperature measurement by this thermoelement is 0.5 °C in the range of -100 °C ÷ 300 °C, according to its manufacturer. This accuracy is in accordance with standard [25].

3.3 Experimental procedure

In temperature calibration experiments, a dry well calibrator (CTD9100-ZERO model) was used. In the first stage of the run, named Experiment No. 1, the temperature gradually increases from 0 °C to 100 °C with a temperature interval of 5 °C for at least 10 minutes to stabilise each preset temperature. In the second stage of the run, named Experiment No. 2, a decreasing temperature was set to find out if hysteresis occurs. During the experiments, the data acquisition station I/OTech DaqLab 2005 [27] with cooperation with DAQView software recorded 300 readings. The measurements were carried out at 1 s time intervals. It should be underlined that both thermoelements were tested in the same measuring channel of the calibrator.

4 Results

4.1 Corrections of temperature measurement by selected thermoelements

Correction of temperature measurement C_{Ti} was determined from the following dependence [28 - 32]:

$$C_{T_i} = \left(t_{ref} - \overline{t_{TC_i}} + C_{DR} + C_{IC}\right) \pm U\left(C_{T_i}\right) \quad (1)$$

where: t_{ref} - the reference temperature, i.e. the preset temperature on the dry well calibrator, $\overline{t_{tC_i}}$ – mean value of the temperature for a tested thermoelement, C_{DR} - correction for the data acquisition station (DaqLab 2005), C_{IC} - correction for the dry well calibrator, $U(C_{Ti})$ - extended uncertainty correction for a tested thermoelement, i - number of the tested thermoelement.

Uncertainty of correction for each tested thermoelement $u\left(C_{T_i}\right)$ is calculated from the following dependence:

$$u\left(C_{T_i}\right) = \sqrt{u^2\left(t_{ref}\right) - u^2\left(t_{TC_i}\right) + u^2\left(t_{Daq}\right)} \quad (2)$$

The uncertainty of measurement resulting from the resolution capability of the data acquisition station $u(t_{Daq})$ was estimated in the publication [33]:

$$u(t_{Daq}) = \frac{0.1}{\sqrt{12}} \quad (3)$$

The uncertainty resulting from the applied etalon $u(t_{ref})$, a dry well calibrator as the instrument for thermoelement calibration, was calculated similarly to [34, 35]:

$$u(t_{ref}) = \frac{U(t_{ref})}{k} \quad (4)$$

where: $U(t_{ref})$ - extended uncertainty of the dry well calibrator, $U(t_{ref})$ = 0.1 ºC or $U(t_{ref})$ = 0.05 ºC in 0 ºC [23], k - expansion coefficient, it was assumed $k = 2$ according to [22, 33, 34].

Tables 2 and 3 show the results of the statistical analysis based on the data from the experiments, including the corrections of the temperature measurement obtained as the difference between the thermoelement measurement (t_{TC1} or t_{TC2}) and the preset reference temperature t_{ref}. Table 2 lists the data from Experiment No. 1 with increasing temperature. Table 3 contains the data from Experiment No. 2 with decreasing temperature. The aim of the authors was to find out if the values of these two experiments varied, indicating that hysteresis occurred.

Table 2. Corrections to temperature measurement by the thermoelements, based on the data from Experiment No. 1 with increasing temperature.

Basic statistical parameters for TC_1	Reference temperature t_{ref} ºC			
	0	**40**	**70**	**100**
n	300	300	300	300
$\overline{t_{TC_1}}$	0.10	39.89	69.94	110.10
$u(C_{T1})$	0.0039	0.0016	0.0042	0.0009
$U(C_{T1})$	0.077	0.0032	0.0085	0.0019
C_{T1}	- 0.096 ± 0.0077	0.108 ± 0.0032	0.058 ± 0.0085	-0.103 ± 0.0019
Basic statistical parameters for TC_2	**Reference temperature t_{ref} ºC**			
	0	**40**	**70**	**100**
n	300	300	300	300
$\overline{t_{TC_2}}$	-0.090	39.92	70.31	100.07
$u(C_{T2})$	0.0036	0.0033	0.0032	0.0032
$U(C_{T2})$	0.0071	0.0066	0.0063	0.0064
C_{T2}	0.090 ± 0.0071	0.085 ± 0.0066	-0.307 ± 0.0063	-0.70 ± 0.0064

Table 3. Corrections to temperature measurement by the thermoelements, based on the data from experiment No. 2 with decreasing temperature.

Basic statistical parameters for TC_1	Reference temperature t_{ref} ºC			
	0	**40**	**70**	**100**
n	300	300	300	300
$\overline{t_{TC_1}}$	0.10	39.92	69.96	100.10
$u(C_{T1})$	0.0039	0.0033	0.0036	0.0009
$U(C_{T1})$	0.077	0.0066	0.0072	0.0019
C_{T1}	- 0.096 ± 0.0077	0.085 ± 0.0066	0.044 ± 0.0072	-0.103 ± 0.0019
Basic statistical parameters for TC_2	**Reference temperature t_{ref} ºC**			
	0	**40**	**70**	**100**
n	300	300	300	300
$\overline{t_{TC_2}}$	-0.09	39.90	70.28	100.59
$u(C_{T2})$	0.0036	0.0036	0.0029	0.0030
$U(C_{T2})$	0.0071	0.0071	0.0058	0.0060
C_{T2}	0.090 ± 0.0071	0.104 ± 0.0071	-0.276 ± 0.0058	-0.590 ± 0.0060

Nomenclature for Tables 2 and 3:
n - sample size,
$\overline{t_{tC_1}}$, $\overline{t_{tC_2}}$ – mean values of the temperature for each thermoelement,
$u(C_{T1})$, $u(C_{T2})$ – uncertainty of correction for each thermoelement,
$U(C_{T1})$, $U(C_{T2})$ – extended uncertainty correction for each thermoelement,
C_{T1}, C_{T2} – correction for each thermoelement.

According to the data shown in Table 2 it was observed that the extremum value of the correction to the temperature measurement was -0.70 ± 0.0064 ºC, while taking into account the results of Experiment No. 1 with increasing temperature. Upon analysis of the results of experiment No. 2 with decreasing temperature, the extremum value of the temperature measurement was -0.59 ± 0.006 ºC, Table 3.

4.2 The relative experimental error and the method accuracy for the thermoelement measurement

The investigations included determining the measurement accuracy for thermoelements of two types, i.e. K-type and T-type. The reference temperature was based on the experimental results recorded with the thermoelements and compared to the preset temperature values on the dry well calibrator CTD9100-ZERO model, according to the calculation method described in detail in [33]. The relative experimental error (*EME*) and the method accuracy (*MA*) were calculated in analogy to [31].

Mean experimental error ($\overline{EME}$) and the confidence interval (*CI*) were determined similarly as in [33], in the following steps:

- calculations of the experimental errors for the measurement due to tested thermoelements;
- determination of the mean values of the experimental errors;
- assumption of the intervals of confidence for the mean values of the experimental errors with normal distribution.

The method accuracy (*MA*) [36] was used to qualitatively assess the accuracy of thermoelement measurement in the tests. Tables 4 and 5 show the results of the statistical analysis, including the relative experimental error obtained by comparing the thermoelement measurements (t_{TC1} and t_{TC2}) with the preset temperature on the dry well calibrator (the reference temperature t_{ref}), based on the data from the experiment with increasing temperature (No. 1) and decreasing temperature (No. 2).

Table 4. The basic statistical parameters of the experimental error and method accuracy, Experiment No. 1 with increasing temperature.

Basic statistical parameters for TC_1	Reference temperature [°C]			
	10	40	70	100
Sample size *n*	300	300	300	300
Min EME	-0.010	-0.0050	-0.0029	0.0010
Max EME	0.00	-0.0025	0.00	0.002
Median	0.00	-0.0025	0.00	0.001
$\overline{EME}$	-0.0014	-0.0027	-0.0008	0.0010
s	0.0034	0.0007	0.0010	0.0002
CI	-0.010 ± 0.068	-0.0027 ± 0.001	-0.0008 ±0.002	0.0010 ± 0.0004
MA	0.82%	0.41%	0.29%	0.13%
Basic statistical parameters for TC_2	**Reference temperature [°C]**			
	10	**40**	**70**	**100**
Sample size *n*	300	300	300	300
Min EME	-0.050	-0.0050	0.0029	0.0050
Max EME	-0.01	0.0025	0.0057	0.008
$\overline{EME}$	-0.0305	-0.0025	0.0044	0.0070
Median	-0.03	-0.0025	0.0043	0.0070
s	0.0056	0.0014	0.0008	0.0006
CI	-0.0305 ± 0.011	-0.0025 ± 0.0028	0.0044 ± 0.0016	0.005 ± 0.0012^{-18}
MA	3.05%	0.21%	0.44%	0.70%

Nomenclature for Tables 4 and 5:
EME – experimental error,
$\overline{EME}$ – mean values of the relative experimental error,
s – experimental standard deviation,
CI – confidence interval,
MA – method accuracy.

Table 5. The basic statistical parameters of the experimental error and method accuracy, Experiment No. 2 with decreasing temperature.

Basic statistical parameters for TC_1	Reference temperature [°C]			
	10	40	70	100
Sample size *n*	300	300	300	300
Min EME	-0.020	-0.0050	-0.0029	0.0010
Max EME	0.020	0.0025	0.0014	0.002
Median	-0.00	-0.0021	-0.000	0.001
$\overline{EME}$	-0.0031	-0.0025	-0.0006	0.001
s	0.0070	0.0014	0.0009	0.0002
CI	-0.0031 ± 0.014	-0.0021 ± 0.0028	0.0014 ±0.0018	0.0010 ± 0.0004
MA	1.70%	0.50%	0.24%	0.13%
Basic statistical parameters for TC_2	**Reference temperature [°C]**			
	10	**40**	**70**	**100**
Sample size *n*	300	300	300	300
Min EME	-0.030	-0.0050	0.0029	0.005
Max EME	0.00	0.0025	0.0057	0.008
$\overline{EME}$	-0.010	-0.0026	0.0039	0.0059
Median	-0.0138	-0.0025	0.0043	0.006
s	0.0064	0.0015	0.0007	0.0005
CI	-0.0138 ± 0.013	-0.0026 ± 0.0030	0.0039 ± 0.0014	0.0059 ± 0.001
MA	1.38%	0.26%	0.39%	0.59%

From the method accuracy (*MA*) results shown in Tables 4 and 5 it is evident that all the parameters obtained for two thermoelements used for the measurement gained similar values. In the case considered, the maximum value of *MA* was less than 3.05 % in the tested temperature range of 0 to 100 °C, while in previous analyses [33] the maximum value of *MA* was less than 4.5% in the same temperature references.

Lower values of basic statistical parameters, especially *EME* and *MA* compared to those obtained from previous statistical analyses [33], were possible because more precise measuring equipment was used during calibration experiments.

Main characteristics of the calibration apparatus for temperature:

- previous calibration experiments: instrument for calibration of the thermoelements, type 9102 HDRC, manufactured by Hart Scientific (USA) [37]:
    - accuracy at the temperature range –10 to 100 °C: ±0.5°C,
    - stability ±0.2°C,
- current calibration experiments: a dry well calibrator (see Table 1), model CDT-9100 ZERO [23].

It should be added that estimating the accuracy of the temperature measurement system in scientific research can reach max. 15% [35].

Furthermore, it was noticed that the values of the relative experimental error (*EME*) and the method accuracy (*MA*) differ depending on whether the temperature increases or decreases during the calibration experiment. It is evidence of the hysteresis phenomenon.

4.3 Estimation of uncertainty of the difference in temperature measurement for tested thermoelements

The difference in temperature Δt between measurements by thermoelements was calculated in analogy to [33].

The uncertainty of the difference in temperature Δt was calculated using the following formula, similarly as in [34, 35]:

$$u(\Delta t) = \sqrt{s^2(\Delta t) + u^2(t_{Daq})} \quad (5)$$

where: $s^2(\Delta t)$ - variance of the difference in temperature measurement, $u(t_{Daq})$ - the uncertainty of measurement temperature resulting from the resolution capability of DaqLab 2005 data acquisition station (Eq. 3).

Confidence interval *CI* was calculated based on the following relationship [34, 35]:

$$CI = \overline{\Delta t} \pm k \cdot u(\Delta t) \quad (6)$$

where: $\overline{\Delta t}$ – mean difference of temperature measurement, k – the expansion coefficient for the level of significance $\alpha = 0.05$, $k = 2$ [34], $u(\Delta t)$ - uncertainty of the difference in temperature measurement (Eq. 5).

The mean difference of temperature measurement t_{ref} - t_{TCi} as a function of the reference temperature t_{ref} is presented in Fig. 4.

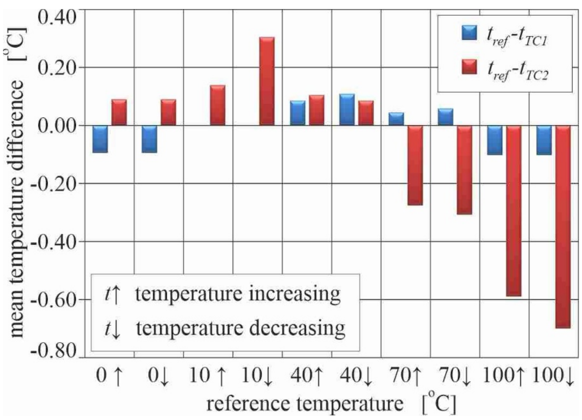

Fig. 4. The mean difference of the temperature measurement t_{ref} - t_{TCi} as a function of the reference temperature t_{ref} where: t_{TCi} - values of temperature measured by *i*-thermoelement.

When analyzing the dependence illustrated in Fig. 4 it was observed that for the highest temperatures (70 °C and 100 °C) the difference in temperature measurement turned out to be the highest, not exceeding ± 0.7 °C.

Table 6 shows the results of the basic statistical parameters in reference to the temperature difference from measurement by thermoelements with preset temperature on a calibrator, while data from Experiment No. 1 with increasing temperature and Experiment No. 2 with decreasing temperature were taken into account, respectively.

Table 6. Basic statistical parameters for the temperature difference.

Basic statistical parameters	Reference temperature - t_{ref} Experiment No. 1 with increasing temperature. °C				
	0	**10**	**40**	**70**	**100**
n	300	300	300	300	300
$\overline{\Delta t}$	0.19	0.29	-0.02	-0.37	-0.60
$u(\Delta t)$	0.10	0.10	0.10	0.10	0.10
$U(\Delta t)$	0.20	0.20	0.20	0.20	0.20
CI	0.19 ±0.20	0.29 ±0.20	0.02 ±0.20	-0.37 ±0.20	-0.6 ±0.20
Basic statistical parameters	**Reference temperature - t_{ref}** Experiment No. 2 with decreasing temperature. °C				
	0	**10**	**40**	**70**	**100**
n	300	300	300	300	300
$\overline{\Delta t}$	0.19	0.11	0.02	-0.32	-0.49
$u(\Delta t)$	0.10	0.10	0.10	0.10	0.10
$U(\Delta t)$	0.20	0.20	0.20	0.20	0.20
CI	0.19 ±0.20	0.11 ±0.20	0.02 ±0.20	-0.32 ±0.20	-0.49 ±0.20

From the analysis of the statistical data shown in Table 6, concerning the difference in temperature measurement, it can be seen that

- values of the uncertainty and the extended uncertainty of the difference in temperature for all reference temperatures reached the same values, while taking into account the results from Experiment No. 1 with increasing temperature and Experiment No. 2 with decreasing temperature;
- the extremum value of the confidence interval of the difference in temperature was -0.6 ± 0.20 ºC, taking into account all results.

It can be underlined that the data vary when comparing the results obtained from Experiment No. 1 (increasing of temperature) and Experiment No. 2 (decreasing of temperature). It is evidence that a hysteresis phenomenon occurred.

5 Conclusions

The main aim of this article was to present the metrology investigations that include the estimation of the uncertainty of contact temperature measurements performed using K- and T-type thermoelements. Contact temperature measurement using thermoelements was realized in experimental investigations on heat transfer during fluid flow in minichannels. A dry well calibrator was used in the temperature calibration experiment. The recording of temperature data was accomplished with the aid of the data acquisition station. The temperatures measured by the thermoelements were statistically compared using the reference temperature preset on the calibrator. In metrology calculations, corrections to the temperature measurement performed by the tested thermoelements were determined. Furthermore, the relative experimental error and the method accuracy for the thermoelement measurement were calculated. The uncertainty of the difference in the temperature measurement for the thermoelements tested with respect to reference temperature was also provided. Statistical analysis was performed on the basis of the collected experimental data. It was noticed that the results vary while comparing the results obtained from the experiment with increasing temperature and the other experiment with decreasing temperature, which is evidence that a hysteresis phenomenon occurred. Furthermore, it was noticed that the values of the relative experimental error (*EME*) and the method accuracy (*MA*) also differed depending on whether the temperature increases or decreases. It confirmed the hysteresis phenomenon. The results of basic statistical parameters, especially *EME* and *MA*, were compared with those obtained from previous statistical analyses based on a calibration experiment with the use of another calibration apparatus.

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