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AN APPROACH TO COLD JUNCTION COMPENSATION AND IDENTIFICATION OF UNKNOWN THERMOCOUPLE TYPE

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The aim of this paper is to present a simple approach to the thermocouple cold junction compensation when the thermocouple type is unknown. The theoretical background of this approach has been explained in the paper. By applying this approach, the voltage-temperature characteristic of the thermocouple has been recorded. A PC-based measurement setup, along with LabVIEW software, has been used for this purpose. The obtained characteristic has been compared with standardised characteristics and the unknown type of the thermocouple has been determined. The results obtained have been presented and analysed in the paper. The results presented could be useful in didactic purposes, as well as for further research in the field.

1. INTRODUCTION

Temperature is the one of the most significant physical quantities that is measured. Over 45 % of all measurement points in industry concern temperature measurement. Despite an increasing variety of temperature sensors, the thermocouple (TC) remains the most commonly used sensor for temperature measurement because of its low cost, wide measurement range, simplicity and easy application [1–5], as well as because of its wide application in electrical engineering, such as testing and techno-economic analysis [6–11].

Nowadays, temperature measurement using TCs can be done using universal measuring instruments for the measurement of electric current and voltage. This temperature measurement is very simple to use. Despite this, the measurement instrument is complex when one takes into account the operation principle of the TC. For proper measurement, it is necessary to choose a suitable type of TC. This mainly depends on the measurement range and other characteristics of TCs, such as the $V(t)$ characteristic and measurement tolerance. For commonly used TCs such as those of type B, E, J, K, N, R, S and T, these characteristics are defined by standards [12]. The standardised $V(t)$ characteristics of these types have been defined exactly by polynomial functions of higher degree rather than by tabulated values [12–14].

This characteristic can change during use [2], which may result in erroneous temperature measurement. Because of this, it is necessary from time to time to check the reading of the thermometer with TC. During this control, it may sometimes occur that the $V(t)$ characteristic of the TC has changed so much that it does not correspond to the standardised one, so the TC type becomes unknown. However, only a few papers have so far been devoted to this issue [15, 16]. In such a case, the cold junction temperature compensation is the main problem which must be solved.

An approach to cold junction compensation (CJC) is presented in this paper. The validity of this approach is tested during the identification of the unknown TC type. Its type is found by comparing its measured and standardised $V(t)$ characteristics. A brief theoretical background of the proposed approach, the measurement setup and results, as well as their analysis, are presented in this paper.

2. THERMOELECTRIC VOLTAGE AND COLD JUNCTION COMPENSATION

Any pair of thermoelectrically dissimilar and electrically conducting materials coupled at an interface is a TC [1]. The Seebeck effect [17] produces a voltage in all such thermoelements if they are not at uniform temperature t. For the TC presented in Fig. 1, the thermoelectric emf $V = \varepsilon t_2$ (which refers to 0 °C) can be calculated as:

$$V = V(t) + V_{ref}, \tag{1}$$

where $V(t) = \varepsilon(t_2 - t_1)$ is the measured voltage, $V_{ref} = \varepsilon t_1$ is the thermoelectric emf of the terminal (cold junction) temperature t_1 and ε is the Seebeck coefficient. The voltage $V(t)$ can be easily measured and the emf V_{ref} can be calculated for a known terminal temperature. If $t_1 = 0$ °C, then $V(t) = V = \varepsilon(t_2 - 0) = \varepsilon t_2$. If $t_1 \neq 0$ °C, then $V(t) = \varepsilon(t_2 - t_1) = \varepsilon t_2 - V_{ref}$. Thus, emf V_{ref} must be added to a measured voltage $V(t)$, *i.e.* compensation must be made, to obtain V.

There are two techniques for implementing CJC - hardware compensation and software compensation [14]. Both techniques require the temperature t_1 at the reference junction to be sensed with a direct-reading sensor. A direct-reading sensor has an output that depends only on the temperature at the measurement point. Semiconductor sensor, thermistor or resistance temperature detector (RTD) (Pt100 and Pt1000) is commonly used to measure the reference-junction temperature. This sensor is located near the screw terminals to which the TC wires are connected.

With hardware compensation, a variable dc voltage source generates a compensation voltage according to the ambient temperature, and thus adds this voltage to the measured one [14]. The major disadvantage of hardware compensation is that each TC type must have a separate compensation circuit that can add the correct compensation voltage, which makes the circuit fairly expensive. Hardware compensation is less accurate than software compensation.

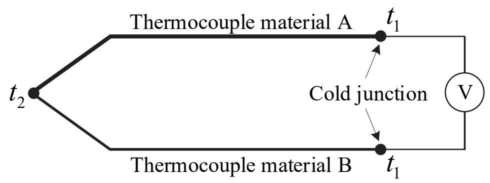

Fig. 1 – Thermoelectric circuit.

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Alternatively, software CJC can be used [14]. After a direct-reading sensor measures the reference-junction temperature t_1, the software calculates and adds the appropriate voltage to the measured voltage to compensate the thermoelectric emf of the terminal temperature. The temperature t_2 can be determined according to the total voltage. Also, the software can calculate the temperature which refers to the measured voltage (without previous compensation). After adding this temperature to the temperature t_1, the temperature t_2 can be determined.

3. AN APPROACH TO COLD JUNCTION COMPENSATION

The TC $V(t)$ characteristic is approximately linear over small deviations in temperature, as presented in Fig. 2a. This figure shows two voltages, V_{st} and $V_{exp}(t)$, as a function of the temperature near the 0 °C point. The first one can be obtained from standardised tables or polynomials and the second by measurement (experiment).

The relations between the voltages shown in Fig. 2 can be written as:

$$V_{st1} = V_{exp}\left(t_1\right) + V_{ref} , \quad (2)$$

$$V_{st2} = V_{exp}\left(t_2\right) + V_{ref} , \quad (3)$$

where t_1 and t_2 are measured temperatures (it is assumed that V_{ref} does not change between measurements). Voltages $V_{exp}(t_1)$ and $V_{exp}(t_2)$ are measured and voltages V_{st1} and V_{st2} are calculated by adding the compensation voltage V_{ref}. As presented in Fig. 2, if the measured temperature is t_0 = 0 °C, then V_{st0} = 0 mV and $V_{exp}(t_0) = -V_{ref}$. Achievement of zero degrees Celsius temperature is not simple, so this measurement usually cannot be performed outside the laboratory. Usually, the temperature is measured at the cold junction with another thermometer. According to this temperature, using the known $V(t)$ characteristic of a certain type of TC, V_{ref} can be calculated. This is the usual CJC. But, such compensation cannot be done if the TC type is unknown.

The approach to CJC is based on the fact that the TC $V(t)$ characteristic is approximately linear near the 0 °C point. Two TCs are needed, one that needs to be identified and one with a known standardised type for temperature measurement (other temperature sensors can also be used instead of this TC). A dc voltmeter with an mV range and a thermometer (or data acquisition system) are also needed. The TC to be identified should be connected to this voltmeter and another TC should be connected to the thermometer. Also, a dry block temperature calibrator is needed. At the beginning of measurement, a lower temperature t_1 should be set at the temperature regulator of the calibrator.

Both TCs are inserted in the dry block, so the temperature t_1 and voltage $V_{exp}(t_1)$ can be measured. Then, temperature t_2, which is only a few degrees Celsius higher than temperature t_1, should be set at the temperature regulator. After this temperature is reached, the temperature t_2 and voltage $V_{exp}(t_2)$ should be measured. Now, a linear part of the $V(t)$ characteristic can be constructed, as presented in Fig. 2b. The intersection of this characteristic with the vertical axis gives a negative voltage which, as previously explained, is the negative value of the compensating voltage V_{ref}. This voltage can be easily calculated by using linear extrapolation. After V_{ref} has been calculated, it can be added to the measured voltage $V_{exp}(t)$ to calculate voltage V_{st}.

4. THERMOCOUPLE TYPE IDENTIFICATION

By using the dry block temperature calibrator, proper temperatures (from low to high) can be set and the desired pairs of temperature and voltage can be measured and used to construct the $V(t)$ characteristic.

This characteristic can be compared with those for standardised TC types (B, E, J, K, N, R, S and T [12]). If the measured characteristic is close to one of the standardised types, then the TC type can be determined. The unknown type corresponds to a standardised type. By this comparison method, the TC identification can be performed. After the identification is done, the standardised $V(t)$ characteristic can be used for new temperature measurement. It may occur that the measured characteristic does not match any of the standardised ones. In this case, it can be concluded that a non-standardised TC has been used or the TC has changed its characteristics over time. The obtained characteristic can be directly used for new temperature measurement.

5. MEASUREMENT SETUP

The measurement setup was based on a personal computer with LabVIEW software and NI cDAQ-9178 chassis with an NI 9211 data acquisition card, as presented in Fig. 3.

A dry block temperature calibrator with temperature regulator was used to obtain the desired temperatures. Actually, two temperature calibrators were used – one for temperatures up to 140 °C and the other for higher temperatures, up to 400 °C. A calibrated TC T_1 (type K) was used for measurement of the temperature in the temperature calibrator, and TCs T_2 and T_3 were identified.

NI 9211 is 24 bits, with four analog input channels, and a data acquisition card made for J, K, T, E, N, B, R and S TCs measurement with embedded CJC. Beside temperature measurement, this card can perform voltage measurement in the range from – 80mV to 80mV.

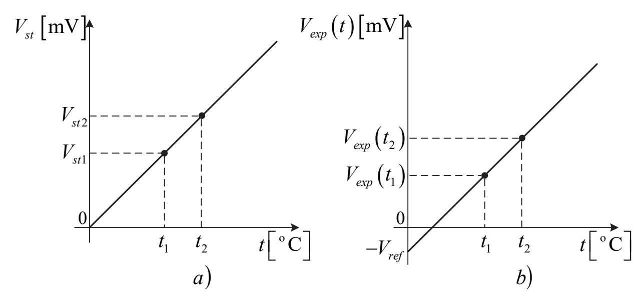


Fig. 2 – Linearized characteristics: a) V_{st}; b) $V_{exp}(t)$.

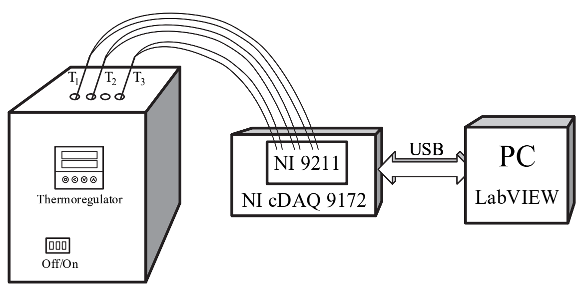


Fig. 3 – Block diagram of measurement setup.

This setup was used for measurements of the voltages and temperatures of interest. LabVIEW application was used to perform all the necessary measurements and calculations and it is described in the following section.

6. LABVIEW APPLICATION AND MEASUREMENT PROCEDURE

The application made in LabVIEW software consists of several parts because each part performs a different measurement procedure. The first part of the application performs CJC based on the proposed approach. The application reads data from data acquisition card inputs, one from TC T_1 in °C and two from TCs T_2 and T_3 in mV. After two sets of temperature and voltages were measured, the application calculated two reference voltages V_{ref1} and V_{ref2}, as shown in Fig. 4 (see also Table 1 in Section 7.1).

In the second part, the application was used for obtaining the $V(t)$ characteristics of TCs T_2 and T_3. These characteristics are presented in tabular and graph form in Fig. 5.

In the third part of the application some arbitrary temperatures were measured by using all three TCs. TC T_1 measures the temperature directly, while the temperatures from T_2 and T_3 were calculated from measured voltages by using previously determined $V(t)$ characteristics by performing the linear interpolation. Also, the absolute and relative deviations between temperatures obtained with TCs T_2 and T_3 and the temperature obtained with T_1 were calculated in this part of the application. Some of the results obtained are presented in tabular form in Fig. 6 (see also Table 2 in Section 7.2).

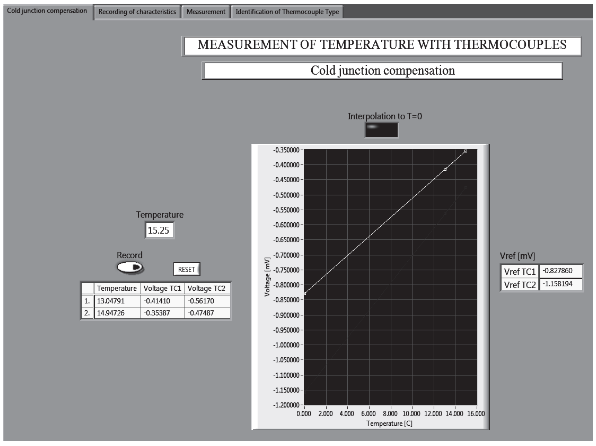


Fig. 4 – LabVIEW application – CJC voltage calculation.

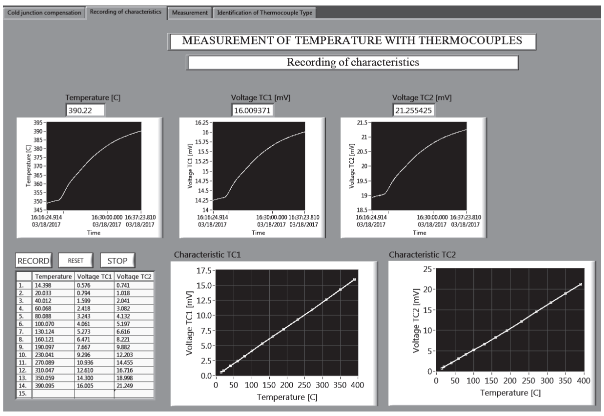


Fig. 5 – LabVIEW application – recording of the $V(t)$ characteristics.

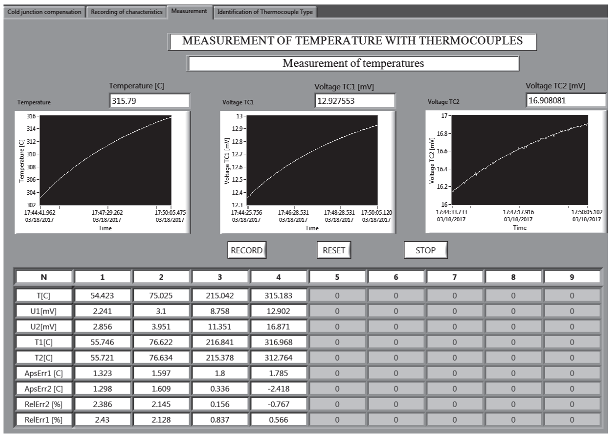


Fig. 6 – LabVIEW application – measurement of arbitrary temperatures and associated deviations.

The final part of the application performs the identification of TCs T_2 and T_3 type by comparison of the obtained $V(t)$ characteristics with the characteristics of the eight standardised TC types (J, K, T, E, N, B, R and S) as in Fig. 7. Comparison was done in three ways: visually, by calculating the mean square error (MSE) and by limit testing. A visual comparison can be made by observing the graph with measured and standardised $V(t)$ characteristics. Calculation of the MSE was done by the following procedure: 1. The application calculates 20 temperatures in the measurement range; 2. it calculates by linear interpolation the corresponding voltages from the $V(t)$ characteristics of two tested and eight standardised TCs; 3. it calculates the *MSE* eight times using voltages obtained from the measured characteristic and voltages obtained from each standardised characteristic. The lowest MSE corresponds to the minimal distance between two series of voltage values and indicates the TC type (see also Table 3 in Section 7.3). Limit testing is illustrated in Fig. 8. The previously calculated 20 values of voltage for each standardised $V(t)$ characteristic are used for creating the upper and lower limits (dashed lines) by adding and subtracting some small voltage (up to several percent) to each of these voltages. Also calculated previously, 20 values of voltage of the tested TC are compared with the created limits. This is repeated eight times for each standardised characteristic. If any value is not within the set limits (Fig. 8*a*), the result of the test is negative (FAILED). If all values are within the set limits (Fig. 8*b*), the result is positive (PASSED), the TC type is identified, and the corresponding message is written in the front panel of the LabVIEW application (Fig. 7).

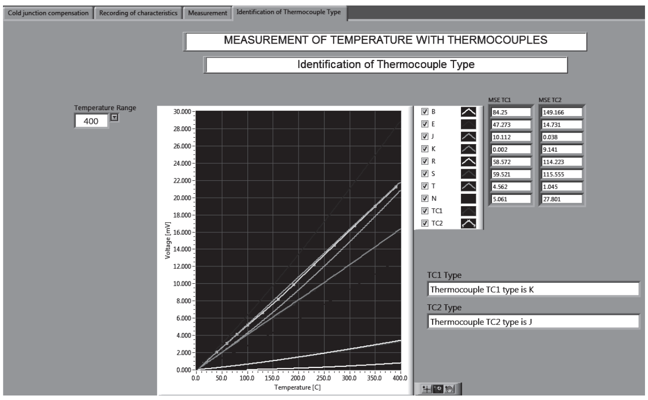
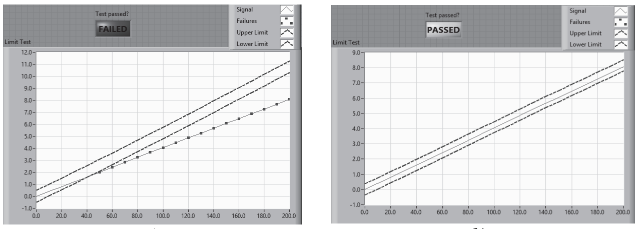


Fig. 7 – LabVIEW application – TC type identification.



a) *b*)

Fig. 8 – LabVIEW application – illustration of limit testing: *a*) negative result, *b*) positive result.

A case can occur when all the limit tests are negative and the TC type is not identified. In such a case, the test can be repeated with increased limits, but the level of this increase is determined with the tolerance classes according to the standard IEC 60584 [12] (see also Table 4 in Section 7.3). Therefore, identification of the TC type is done by the limit testing, up to some tolerance, and it needs to be confirmed with the MSE value and with visual inspection. The TC type is determined if and only if all three are positive.

If desired, the final report of these measurements can be printed. This report contains the $V(t)$ characteristic of T_2 and T_3, results for arbitrary temperatures and the obtained deviations, determined types of TCs, current date and time, and other.

The application was designed to be effective for all measurements described, without knowing the type of TCs T_2 and T_3. It can be used in the same way also if these types are known. Moreover, with some minor changes, the application can be used (the first and the second part need to be skipped) and direct measurement of the temperatures with T_1, T_2 and T_3 can be performed. This can be used for calibration of T_2 and T_3.

7. MEASUREMENT RESULTS

The results obtained from the measurements are presented in this section. In order to confirm the applicability of the proposed measurement procedure, especially the CJC calculation procedure, five TCs with known type and one TC with unknown type (type X) were used in the experiments. These five TCs are of the following types: T, N, J, K [12] and L (similar to type J; described in former standard DIN 43710). However, all the measurements were performed so that these types were not taken into account at the beginning of the measurement. Therefore, all six TCs were tested according to the measurement procedure described in the previous section.

Depending on the TC measurement range, measurements were performed at different temperature ranges, as follows:

1. types K and L – up to 400 °C,
2. types T and N – up to 140 °C, and
3. types J and X – up to 200 °C.

Measurements were repeated three times, each time with two TCs of the same range, and six TC characteristics were identified in these measurements.

7.1. COLD JUNCTION COMPENSATION

Table 1 summarises all the results of measurements related to the CJC. CJC was performed by the proposed approach, as presented in Fig. 2. At two relatively low temperatures, TC voltages were measured. The reference voltages V_{ref} were calculated using linear extrapolation.

Table 1

Measured cold-junction compensation voltages

Type	K	L	T	N	J	X
t_1 [°C]	12.36		12.96		13.05	
t_2 [°C]	14.36		14.92		14.95	
V_{ref} [mV]	1.128	1.439	1.163	0.789	1.158	0.828

7.2. RECORDING OF $V(t)$ CHARACTERISTICS AND MEASUREMENT OF ARBITRARY TEMPERATURES

The measured $V(t)$ characteristics of all six TCs are presented in the graphs in Fig. 9.

Measurements of arbitrary temperatures were done using these $V(t)$ characteristics. The results for the measured temperatures and absolute deviations of these temperatures relative to the one measured with the calibrated TC are presented in Table 2. Temperature t_1 was measured with the calibrated TC, voltages V_2 and V_3 were measured with the tested TCs, temperatures t_2 and t_3 were calculated according to previously measured $V(t)$ characteristics and $\Delta t_2 = t_2 - t_1$ and $\Delta t_3 = t_3 - t_1$ are the corresponding absolute deviations.

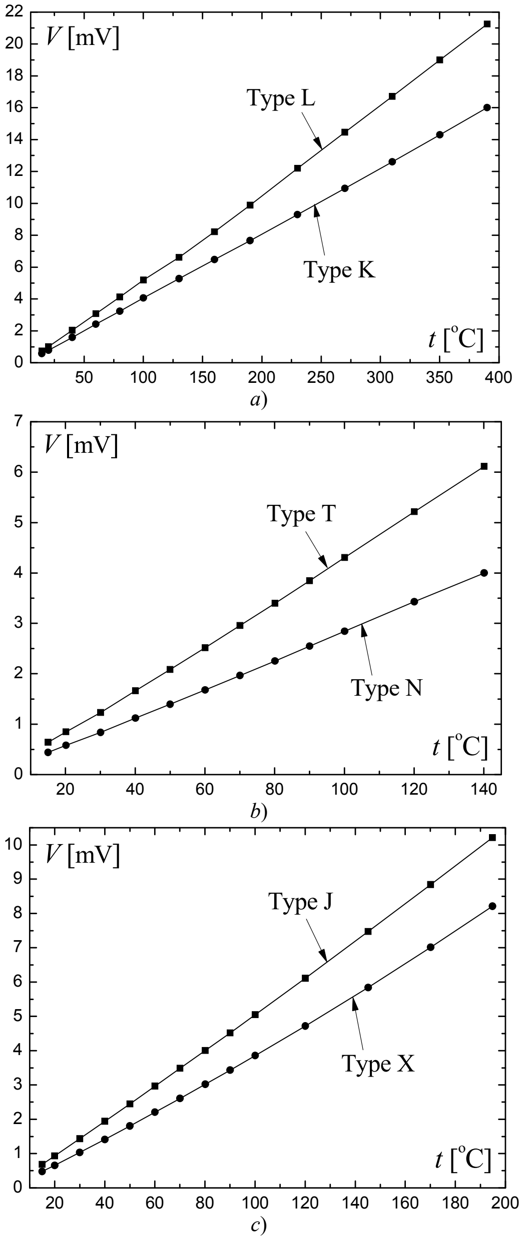


Fig. 9 – Measured $V(t)$ characteristics: a) types K and L; b) types T and N; c) types X and J.

Table 2

Measured arbitrary temperatures

Types	t_1 [°C]	V_2 [mV]	V_3 [mV]	t_2 [°C]	t_3 [°C]	Δt_2 [°C]	Δt_3 [°C]
K and L	54.4	2.24	2.86	55.7	55.7	1.3	1.3
	75.0	3.10	3.95	76.6	76.6	1.6	1.6
	215.0	8.76	11.35	216.8	215.4	1.8	0.4
	315.2	12.90	16.87	317.0	312.8	1.8	−2.4
T and N	50.1	2.11	1.41	50.5	50.6	0.4	0.5
	70.0	2.97	1.98	70.3	70.3	0.3	0.3
	100.0	4.32	2.85	100.5	100.3	0.5	0.3
J and X	40.9	1.34	1.88	38.2	38.2	−2.7	−2.7
	49.0	1.68	2.29	47.0	46.8	−2.0	−2.2
	74.1	2.72	3.62	72.8	72.7	−1.3	−1.4

The obtained absolute deviations are mostly within the tolerances given in the standard [12], except one amounting to −2.7 °C obtained at 40.9 °C with types J and X (the standard tolerance for type J is ± 2.5 °C). Therefore, the measured $V(t)$ characteristics are in good agreement with the standardised ones. This also indicates the validity of the proposed CJC method.

7.3. THERMOCOUPLES TYPE IDENTIFICATION

Figure 10 presents a comparison of the measured $V(t)$ characteristics of all six tested TCs and the $V(t)$ characteristics of the standardised TC types B, E, J, K, N, R, S and T at the corresponding ranges. From the presented graphs, it can be observed that the recorded characteristics are in very good agreement with the standardised characteristics. The TC types can be identified according to these graphs.

However, the identification should be confirmed not only visually but with some numerical results. This paper proposes two ways of numerical TC identification: by calculation of the mean square error (MSE) and by limit testing. Also, a validation of identification using the regression analysis, such as the coefficient of determination (R squared) and other, can be applied.

The MSE was calculated according to the following expression:

$$\mathrm{MSE} = \frac{1}{N}\sum_{i=1}^{N}\left(V_{Si} - V_{ti}\right)^2 , \quad (4)$$

where V_{Si} is the voltage corresponding to the temperature t_i obtained from the $V(t)$ characteristic of the standardised TC, V_{ti} is the voltage corresponding to the temperature t_i obtained from the measured $V(t)$ characteristic of the tested TC, $N = 20$ is the total number of temperatures t_i used in the calculation. The MSE was calculated for eight standardised TC types (B, E, J, K, N, R, S and T) and the minimal *MSE* indicated the type of the tested TC. In ideal matching of two $V(t)$ characteristics, the MSE is equal to zero. However, this result cannot be achieved in a real experiment and for appropriate identification it is reasonable to expect very small values of MSE (such as 0.01 or 0.04), as presented in Table 3. In this table, the bold numbers in each row are the minimal values of MSE and they are indicators of the tested TC type. As can be seen in Table 3, two or three values of MSE can be small (mostly expressed in column T). The reason is the small difference of two standardised $V(t)$ characteristics (T and K, Fig. 10*b*) in the corresponding temperature range (140 °C).

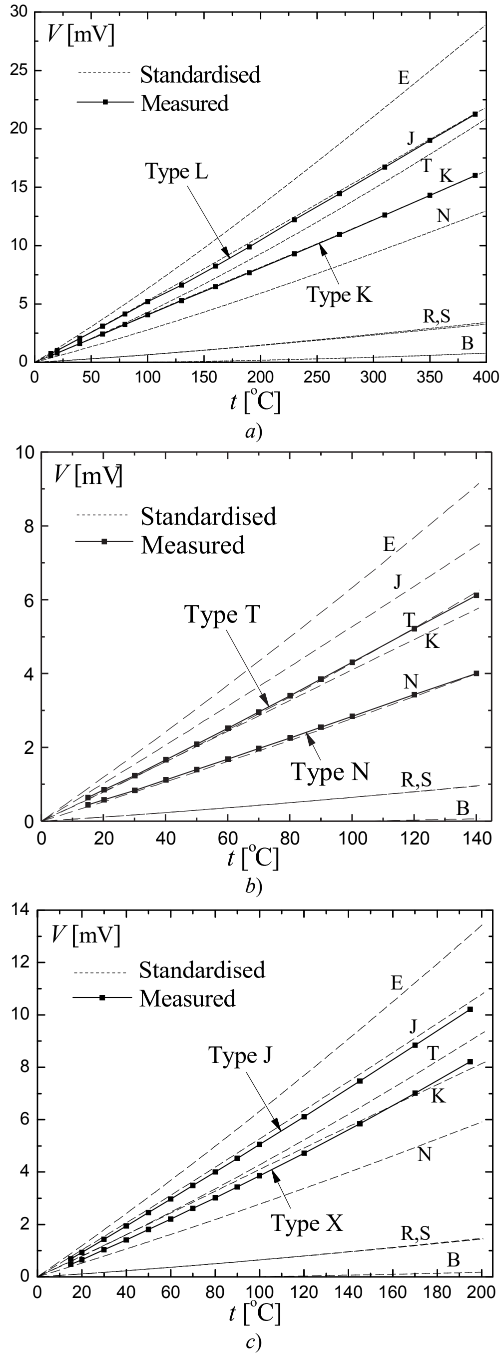


Fig. 10 – Comparison of $V(t)$ characteristics of two measured (solid lines, squares and arrows) and eight standardised (dashed lines, marked with letters): a) types K and L; b) types T and N; c) types X and J.

Table 3

Calculated mean square errors

Standard type \ Tested type	MSE [(mV)^2] K	L	T	N	J	X
B	84.25	149.17	12.21	5.27	35.48	21.81
E	47.27	14.73	2.79	8.24	2.59	8.39
J	10.11	**0.04**	0.63	3.97	**0.04**	2.26
K	**0.01**	9.14	0.03	1.04	1.59	**0.04**
R	58.57	114.22	8.94	3.21	27.23	15.45
S	59.52	115.55	8.96	3.21	27.33	15.53
T	4.56	1.045	**0.01**	1.44	0.64	0.24
N	5.06	27.80	1.55	**0.01**	7.14	1.92

Limit testing has been previously described and illustrated in Fig. 8. During this testing, an upper and lower limit were set in such a way that two lines parallel to the $V(t)$ characteristic of the standardised TC type were created (one above and one below). Both limits are at the same small distance from the $V(t)$ characteristic. The measured $V(t)$ characteristic of the tested TC should be inside these limits to have a positive TC type identification. Also, the test needs to be positive only for one standardised $V(t)$ characteristic. The testing was repeated until the minimum distance was determined. This distance is represented as a percental value of the corresponding voltage of the standardised TC type. The lower this minimal limit is, the closer the recorded $V(t)$ characteristic is to the standardised $V(t)$ characteristic. The values of the minimal limit and the type identified for the tested TCs are presented in Table 4.

According to the graphs given in Fig. 10 and the results in Tables 3 and 4, a successful identification of type was performed for all six tested TCs. Four TCs of known type were identified with their original type, while one TC of known type L was identified as type J. This identification can be considered successful because the $V(t)$ characteristics of TC types L and J are almost identical. In the case of the TC of unknown type (type X), the identification was also successful and this TC was identified as type K. However, according to the graph presented in Fig. 10*c* and the result of limit testing given in Table 4 (last column), it can be seen that a noticeable difference between $V(t)$ characteristics exists. In any case and in this case also, the identification is valid only in the corresponding temperature range. Generalisation to a wider temperature range should not be made. Therefore, in the last case, the TC can be used in further measurements as standardised type K, or it can be used as an unstandardised type with the previously obtained $V(t)$ characteristic, but only for temperatures up to 200 °C.

In addition to the identification of an unknown TC type, the proposed CJC method can be used in the calibration of a TC of known type. This can be done by following the procedure described in Sections 3–5 without producing a zero temperature (0 °C) and without the additional thermistor for measurement of the reference-junction temperature. However, the implementation of such a CJC needs to be carefully considered and put in accordance with calibration references, such as [18].

8. CONCLUSIONS

An approach to cold junction compensation for thermocouples has been proposed in this paper. This approach is general since it can be used for any type of TC. Especially, it can be used when the TC type is unknown. Also, this approach is simple, it can be easily implemented, it is not time-consuming and it requires no additional costs.

In this paper, the approach to CJC was implemented using a PC-based measurement setup. Data acquisition cards and a LabVIEW application were used for performing all measurements. This equipment was used for the identification of unknown TCs. Their $V(t)$ characteristics were recorded and the arbitrary temperatures were measured using these characteristics. Relative deviations of the obtained results were calculated. Almost all the deviations were within standard tolerances.

Table 4

Calculated limits

Type	K	L	T	N	J	X
Min. limit [%]	±0.50	±1.60	±1.55	±1.75	±2.65	±4.00
Identified type	K	J	T	N	J	K

The obtained characteristics were compared with the standardised characteristics of B, E, J, K, N, R, S and T types of TC and the unknown TC was identified.

The results presented in this paper are very useful for teachers and students interested in temperature measurement with thermocouples. They can collect new theoretical and practical knowledge on thermocouples, measurement methods and equipment, as well as software tools for the development of virtual instruments.

Furthermore, the proposed CJC approach and the results presented may encourage other researchers to devote more attention to this subject and to propose other CJC approaches and their practical implementation.

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REFERENCES

1. J.G. Webster, *The Measurement, Instrumentation and Sensors Handbook*, CRC Press, London, 1999.
2. M. Nau, *Electrical Temperature Measurement with Thermocouples and Resistance Thermometers*, M.K. Juchheim, Fulda, 2002.
3. P.R.N. Childs, J.R. Greenwood, C.A. Long, *Review of Temperature Measurement*, Rev. Sci. Instrum., **71**, *8*, pp. 2959–2978 (2000).
4. L. Michalski, K. Eckersdorf, J. Kucharski, J. McGhee, *Temperature Measurement*, John Wiley and Sons, Weinheim, 2001.
5. G.W. Burns, M.G. Scroger, *The Calibration of Thermocouples and Thermocouples Materials*, National Institute of Standards and Technology, Washington, 1989.
6. A. Floriduz, E. Bassi, F. Benzi, G. Secondo, P.S. Termini, *Wireless Temperature Sensing in Electrical Motors with XBee Modules*, IEEE Workshop on Electrical Machines Design, Control and Diagnosis, Torino, Italy, 26-27 March 2015, pp. 304–308.
7. D. Susa, M. Lehtonen, H. Nordman, *Dynamic Thermal Modeling of Distribution Transformers*, IEEE Transactions on Power Delivery, **20**, *3*, pp. 1919–1929 (2005).
8. R. Mocanu, A. Onea, *Determination of Stator Temperature for Thermal Protection in a Permanent Magnet Synchronous Machine*, 25th Mediterranean Conference on Control and Automation, Valletta, Malta, 03-06 July 2017, pp. 1321–1325.
9. S. Purushothaman, F. de León, *Heat-Transfer Model for Toroidal Transformers*, IEEE Transactions on Power Delivery, **27**, *2*, pp. 813–820 (2012).
10. M. Daghrah, Z.D. Wang, Q. Liu, D. Walker, C. Krause, G. Wilson, *Experimental Investigation of Hot Spot Factor for Assessing Hot Spot Temperature in Transformers*, International Conference on Condition Monitoring and Diagnosis, Xi'an, China, 25-28 Sept. 2016, pp. 948–951.
11. S. Aleksandrović, M. Jović, *Economic and Technical Aspects of Transformer Operation*, Energy Sources, Part B: Economics, Planning, and Policy, **11**, *1*, pp. 26–31 (2016).
12. IEC 60584-1 - Ed. 3.0 - *Thermocouples - Part 1: EMF Specifications and Tolerances*, IEC, Geneva, 2013.
13. http://srdata.nist.gov/its90/download/download.html.
14. D. Potter: *Measuring Temperature with Thermocouples – A Tutorial*, National Instruments Application Note 043, Nov. 1996.
15. P. Kundu, G. Sarkar, *Type Identification of Unknown Thermocouple Using Principle Component Analysis*, Sens. Transd., **114**, *3*, pp. 112–121 (2010).
16. S.K. Damarla, P. Kundu, *Classification of Unknown Thermocouple Types using Similarity Factor Measurement*, Sens. Transd., **124**, *1*, pp. 11–18 (2011).
17. A.M. Morega, M. Morega, M.A. Panait: *Structural Optimization of a Thermoelectric Generator by Numerical Simulation*, Rev. Roum. Sci. Techn. – Électrotechn. et Énerg., **55**, *1*, pp. 3–12, (2010).
18. EURAMET, *Calibration of Thermocouples*, CG-8, Version 2.1, Oct. 2011.