Method of Thermocouples Self Verification on Operation Place

1 Chang SHU, 2 Orest KOCHAN
1 School of Economics Management, Northwest University of Politics and Law, Xi’an, Shaanxi, 710063, China.
2 Department of Metal Physics, Ivan Franko National University of L'viv, Universytetska str., 1, Lviv, 79000, Ukraine
E-mail: orestvk@gmail.com

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Abstract: The method of periodic verification in operation condition of the main thermocouple of thermocouple based sensor with controlled profile of temperature field (TBS with CPTP) is proposed in this paper. This periodic verification can be done without dismantling out of sensor from operation place as well as without any working standards. The reference thermocouples of either 1st or 3rd level of hierarchy scheme can be used for verification of TBS with CPTP right after produce. Evaluation of self verification error in this case has shown value of error at either 1 ºC or 1.2 ºC respectively.

Keywords: Temperature calibrator, Frequent verification.

1. Introduction

Thermocouples (TC) are widely used sensors in measuring temperatures above 600 °C. However, they have long been the least reliable and accurate part of measuring channel. Errors of common standardized TC for the last decades have not become smaller. The major disadvantages of TC are:

- The initial deviation of the conversion characteristic (CC) from nominal is quite large. For the most common K-type TC, it reaches 5.5 ºC at 600 ºC, and 8 ºC at 1100 ºC [1].
- There is a big drift of CC during long-term operation at high temperatures. For K-type TC it reaches 0.5 ºC at 600 ºC, and 10 ºC at 1100 ºC for 1000 hours of operation [2, 3];
- A thermoelectric inhomogeneity of TC electrodes acquired during operation time at high temperature is also large. For K-type TC, the error reaches 2 ºC at 600 ºC and 11 ºC at 1100 ºC for 1000 hours of operation [4].

The last disadvantage has led to the hasty conclusion about the impossibility of correction errors of TC, which have been in use [6]. However, methods of error correction of such TC have appeared recently. Therefore, let’s take a look at the possibilities to improve the accuracy of temperature measurement, using TC

1.1. Analysis of Methods for Improving the Accuracy of Thermocouples

Development of new alloys for TC electrodes has not led to a significant increase in accuracy of TC. Correcting methods can be divided into two groups:

1. The ones, that require stationary profile of the temperature field of measurement object during the operation TC;
2. The ones, that take into account possible change of the temperature field profile along the TC electrodes.
The first group includes a frequent verification of TC in lab, and use of obtained errors as amendments. This method has a significant acquired inhomogeneity. The best methods are:

1. Verification on operation place using reference TC. It has to be inserted into an additional channel of temperature sensor [2];
2. Calibration using temperature calibrator. Calibrator is a hermetical capsule that contains either pure metal or alloy inside with a known temperature of phase transition (melting / solidification). It is located at the hot junction of TC and creates a temperature plateau at the time of the phase transition [5].

Additional increase of accuracy of temperature measurement, while reducing the complexity, is possible by constructing an error model of TC for its individual prognosis during operation process [8]. However, the above mentioned methods require a new verification or calibration during the profile change of the temperature field of the temperature measurement object. Otherwise, an error from acquired thermoelectric inhomogeneity will not lead to the accuracy increase of temperature measurement.

Inhomogeneity of thermocouples leads to an additional error when temperature field changes. It was proposed to provide verification of TC in a few profiles of temperature field [7] for TC error correction in this case. Such verification allows to determine coefficients for individual models of drift of CC of each section of TC. Recognition properties of neural networks are used for decreasing of points of verification.

Substantial increase in accuracy at operation in condition of unstable temperature field provides thermocouple based sensor with controlled profile of temperature field (TBS with CPTF) [8]. In TBS with CPTF the profile of the temperature field along the electrodes of the main thermocouple (MTC) is stabilized by additional control systems. Such systems include additional TC, heaters and multichannel control system. This solution also allows us to set a necessary profile of the temperature field along the electrodes of MTC during the operation. This creates additional possibilities to improve the accuracy of temperature measurement.

The purpose of the article is to develop a method of periodic self-verification MTC of TBS with CPTF on operation place without additional means. This method will enable the use of methods [6, 7] to improve the accuracy of temperature measurements in condition of variable temperature field profile of the measurement object.

2. The Theoretical Basis of the Proposed Method

Let TC electrodes operate in the temperature field, which is described by monotonic dependence. We divide each TC electrode into zones \( i = 1, n \).

Electromotive force (EMF) \( E_k \) for \( k \) zone can be written as

\[
E_k = (e_N + \Delta e_k) \cdot (t_{k+1} - t_k),
\]

where \( e_N, \Delta e_k \) are the nominal value of the specific EMF of the given electrode material and its individual deviation for \( k \) area; \( t_{k+1}, t_k \) – temperature boundaries of the \( k \) electrode zone.

If the difference \( t_{k+1} - t_k \) approaches to zero, total EMF \( E_\Sigma \) of one electrode will be

\[
E_\Sigma = E_N + \frac{1}{0} \Delta e_k dt,
\]

where \( E_N \) is the nominal value of EMF, which generates each electrode under affect of given temperature difference \( t_{k+1} - t_0 \). Integral determines the total error of the electrode \( \Delta E_\Sigma \).

During the operation time \( T \), electrodes change its chemical composition (oxidation, migration) and crystalline structure under the influence of high temperatures. Intensity of changes considerably depends on the operation temperature \( t_e \) of each zone [7-9], which means that \( \Delta e_k = \Delta e(t_e, \tau) \).

According to (2) it is possible to find a total error \( \Delta E_\Sigma \) of electrode with certain profile of operation temperature field. [9]

\[
\Delta E_\Sigma = \int_0^{t_{k+1}} \Delta e_k dt = \int_0^l \Delta e(t_e, \tau) \frac{\partial t}{\partial l} dl =
\]

From (3) the following conclusions can be derived [9]:

1. If \( \frac{\partial t}{\partial l} \to 0 \), then \( \Delta E_\Sigma \to 0 \). Drift \( \Delta e_k = \Delta e(t_e, \tau) \) of TC’s zones, which are being used at a temperature field without gradient (zones \( t_0 \ldots t_3 \) and \( t_4 \ldots t_7 \) of the curve A from the Fig. 1), does not cause errors in the measurement result.

2. If \( \Delta e(t_e, \tau) \to 0 \), then \( \Delta E_\Sigma \to 0 \). Drift of zones, which are used at the temperature of cold junctions \( t_C \) (zones \( t_0 \ldots t_3 \) of curve A on the fig. 1), is absent. It does not cause errors in the measurement result.
3. If $\Delta e_k = \Delta e(t_e, \tau)$ and $\Delta e \approx k \cdot t_e$ (drift is proportional to the operation temperature [2, 3]), then $0 < \Delta E_{\Sigma} < \Delta E_{\Sigma}^{MAX}$. Total drift of the zones, that are used in the gradient of the temperature field (zones $l_1 \ldots l_4$ of the curve A on the Fig. 1), has an average value. This total drift is formed by zones at different temperatures - from minimum to maximum.

4. If $\Delta e_k = \Delta e(t_e, \tau)$ and $\Delta e \approx k \cdot t_e$, then the maximum value of electrodes drift $\Delta E_{\Sigma}^{MAX}$ can be determined in the profile of electrodes drift of the curve B (Fig. 1). Then the $l_5 \ldots l_6$ zones, which create EMF, previously have been used at the maximum temperature (temperature of the hot junction $t_{RU}$). That is why they have a maximum deviation of the specific EMF $\Delta e_k$ from their initial value before operation, which means that $\Delta e_k \rightarrow \max$.

5. If $\Delta e_k = \Delta e(t_e, \tau)$ and $\Delta e \approx k \cdot t_e$, then $\Delta e_k \rightarrow 0$ when moving the electrodes to the temperature field of the curve C (Fig. 1). Zones $l_0 \ldots l_3$, which have not been operated at the high temperature generate EMF. These zones were at the temperature of cold junctions $t_{CJ}$. This refers to paragraph 2. Therefore, the result of measuring the temperature in this case is free from drift of thermocouple CC.

The last conclusion can serve as a basis for the method of self verification of TC on operation place [10].

### 3. Realization of the Method of Self Verification of Thermocouples

The realization of the proposed method of TBS with CPTF self verification on operation place involves finding the difference between EMF $E_A$ in the temperature field of the curve A and EMF in the temperature field of the curve C (Fig. 1). EMF $E_A$ includes drift error $\Delta E_A$ of zones $l_3 \ldots l_4$ in the operation temperature field. EMF $E_c$ is free from drift error. Zones $l_1 \ldots l_2$ are used at low temperature of cold junctions $t_{CJ}$. Their drift is relatively small.

TBS with CPTF provides control of temperature field profile. Therefore, the proposed method of self verification can be implemented. Conditions of this verification method are:

1. Constancy of hot junction $t_{RU}$ and cold junctions $t_{CJ}$ temperatures during verification period.
2. Sufficient “shift” of temperature field gradient ($l_2 \ldots l_3 > 0$).

To improve the accuracy of temperature measurement, it is necessary to eliminate the error of initial deviation of individual CC of $l_1 \ldots l_2$ zones from nominal one. To achieve this, TBS with CPTF has to be checked at manufacture using reference TC.

At the same time, zones $l_1 \ldots l_2$ (profile C of temperature field, Fig. 1) should generate an EMF. The same zones will generate an EMF during self verification. Therefore, we can eliminate the influence of error of the initial deviation of CC from initial one on the result of verification.

A process of TBS with CPTF’s metrological service with self verification is illustrated on Fig. 2. At the manufacture of TBS with CPTF, the verification is done in profile of the temperature field using reference TC (Fig. 2a). This takes into account individual deviations of CC of $l_0 \ldots l_1$ zones from nominal one. According to (3), the following expression can be written

$$\Delta E_{\Sigma} = \int \Delta e(t_e, \tau, t) \frac{\partial t}{\partial l} dl + \int \Delta e(t_e, \tau, 0) \frac{\partial t}{\partial l} dl + \int \Delta e(t_e, \tau, t) \frac{\partial t}{\partial l} dl$$

$$+ \int \Delta e(t_e, \tau, 0) \frac{\partial t}{\partial l} dl \, (4)$$

where $l_0 \ldots l_4$ are the MTC’s zones according to fig. 2; $\Delta e_1(t_e, \tau) \ldots \Delta e_4(t_e, \tau)$ - individual deviations of the specific EMF of MTC areas according to Fig. 2.

At the beginning of operation (during the initial verification) $\tau = 0$. According to paragraph 1, if $\frac{\partial t}{\partial l} \rightarrow 0$, then $\Delta E_{\Sigma} \rightarrow 0$. Therefore, following expression can be written

$$\Delta e_2(t_e, \tau, 0) = \Delta e_3(t_e, \tau, 0) = \Delta e_4(t_e, \tau, 0) = 0 \, (5)$$

and convert (4)

$$\Delta E_{\Sigma}^{FT} = \int_{l_0}^{l_4} \Delta e_1(t_e, \tau, 0) \frac{\partial t}{\partial l} dl \, (6)$$

Fig. 1. Profiles of the temperature field along the thermocouple electrodes.
where $\Delta E^{PT}_\Sigma$ is the result of the initial verification (individual deviation of CC of $l_0 \ldots l_1$ zones from the initial on

![Fig. 2. Process of metrological service of TBS with CPTF during the work cycle.](image)

Further the TBS with CPTF operates in the profile of the temperature field shown on Fig. 2 (b). Suppose the operation time is $\tau = \tau_1$. At the same time, the zones $l_2 \ldots l_4$ drift. In contradiction to (5), $\Delta e_3(t_e, \tau_1) \neq \Delta e_4(t_e, \tau_1) \neq 0$. The zones $l_0 \ldots l_2$ are located at the temperature $t_{CJ}$ and do not drift. Then, $\Delta e_1(t_e, \tau_1) = \Delta e_2(t_e, \tau_1) = 0$. However, for zones $l_3 \ldots l_4$ the gradient $\frac{\partial \tau}{\partial l} \rightarrow 0$. Therefore, $E_{13\ldots44} \rightarrow 0$ and drift of the zones $l_3 \ldots l_4$ does not affect the error of the total EMF. For this case, the following can be written similar to (6)

$$\Delta E^E_\Sigma = \int_{l_2}^{l_3} \Delta e_3(t_e, \tau_1) \frac{\partial t}{\partial l} dl, \quad (7)$$

where $\Delta E^E_\Sigma$ is the error of individual deviation of CC of zones $l_2 \ldots l_3$ from initial one during the operation time, for time $\tau = \tau_1$ (including the time drift due to the effect of high operation temperature).

Periodic verification of TBS with CPTF is done under the following conditions:

1. Temperature of the hot junction of MTC $t_{HJ}$ has not changed for some time;
2. We can expect the absence of changes of temperature $t_{HJ}$ during 20…30 minutes.

To provide periodic verification of TBS with CPTF, profile of the temperature field has to be set according to Fig. 2(c). This profile should be the same as the profile of temperature field of the initial verification (Fig. 2(a)). In this case, $\Delta e_3(t_e, \tau_1) \neq \Delta e_4(t_e, \tau_1) \neq 0$.

However, for zones $l_1 \ldots l_4 : \partial t/\partial l \rightarrow 0$. That is why, if $E_{13\ldots44} \rightarrow 0$, then the zones $l_1 \ldots l_4$ do not affect on the total EMF of MTC. Therefore, the result of periodic verification $\Delta E^{PT}_\Sigma$ can be derived as

$$\Delta E^{PT}_\Sigma = \int_{l_0}^{l_1} \Delta e_1(t_e, \tau_1) \frac{\partial t}{\partial l} dl \quad (8)$$

We can assume in the first approximation that $\Delta e_1(t_e, \tau_1) = \Delta e_1(t_e, \tau_0)$, because the zones $l_0 \ldots l_1$ were at high temperature for a short period of time (just for a time of self verification), and the (8) completely corresponds to (6).

The error of the proposed method of self verification will be evaluated in camera ready.

4. Estimation of the Error of Self verification

Analysis of (4), (6)... (8) allows to identify error sources of self verification of TBS with CPTF. During the first verification (just after produce) the main error sources are following reasons:

1. Reference thermocouple error of the primary verification $\Delta_{R}$. This error depends from the status of the reference thermocouple. Error range is $0.3 – 0.6 \, ^\circ C$ [11].
2. Measurement of e.m.f. error of reference thermocouple $\Delta^{E}_{R}$. For high-quality measurement systems its magnitude doesn’t exceed 0.4 °C. So $\Delta^{E}_{R} \leq 0.4^\circ C$ [12].
3. Cold junction temperature correction error of the reference thermocouple $\Delta^{CJ}_{R}$. Typical value of this error for high-quality is $\Delta^{CJ}_{R} \leq 0.1^\circ C$ [13].
4. Temperature determination after e.m.f. of the reference thermocouple error $\Delta^{LIN}_{R}$ (linearization and errors correction). For high-quality microcontroller-based measurement systems its magnitude $\Delta^{LIN}_{R} \leq 0.1^\circ C$ [12].
5. E.m.f. measurement error $\Delta^{E}_{X}$ of the produced thermocouple. For type K thermocouples $\Delta^{E}_{X} \leq 0.1^\circ C$ [12].
6. Cold junction temperature correction error of the produced thermocouple $\Delta^{CJ}_{X}$. For high-quality measurement systems $\Delta^{CJ}_{X} \leq 0.1^\circ C$ [13].
7. Temperature determination after e.m.f. of the produced thermocouple error $\Delta_{LX}^{TN}$ (linearization and errors correction). For high-quality microcontroller-based measurement systems its magnitude $\Delta_{LX}^{TN} \leq 0.1^\circ C$ [12].

8. Error due to inadequacy of a cold junction temperature of the reference thermocouple and $\Delta_{X}^{PT} \leq 0,1^\circ C$ [13] if a nickel temperature leveling device is used.

$$
\Delta_{X}^{PT} = \sqrt{\Delta R^2 + \Delta E^2 + \Delta C_{J}^2 + \Delta_{LX}^{LIN^2} + \Delta_{E}^{CJ^2} + \Delta_{LX}^{LIN^2} + \Delta_{E}^{D^2} + \Delta_{R}^{2} + \Delta_{X}^{2}}
$$

Putting to the formula (9) corresponding errors mentioned above, we get $\Delta_{X}^{PT} \leq 0.6...0.8^\circ C$ (exact value depends on which status of the reference thermocouple is used)

The main error sources during the periodical testing are following:

1. Reference device error that is used for periodical verification $\Delta_{R}^{PT}$. In other words zones $I_0 \cdots I_1$ of the MTC for proposed self verification method. This error analysis is given below.

2. E.m.f. measurement error $\Delta_{X}^{E}$ of a thermocouple that is verified. For high-quality measurement systems $\Delta_{X}^{E} \leq 0.1^\circ C$ [12].

3. Cold junction temperature correction error of a thermocouple that is verified. For high-quality measurement systems $\Delta_{X}^{CJ} \leq 0.1^\circ C$ [13].

4. Temperature determination after e.m.f. of a thermocouple that is verified $\Delta_{X}^{LIN}$ (linearization and errors correction). For high-quality microcontroller-based measurement systems $\Delta_{X}^{LIN} \leq 0.1^\circ C$ [12].

5. Error due to hot junction temperature change of a thermocouple that is verified $\Delta_{X}^{HJDT}$. This error depends from chosen instant of a self verification. It can’t be estimated precisely. It is necessary to measure temperature of an object before and after self verification for its estimation. A tolerant difference may be estimated using tolerant range of a self verification error. It is necessary to repeat self verification one more time if this difference exceeds tolerance limits. Analysis of temperature changes in big power plant furnaces showed that magnitude of this error is limited by $\Delta_{X}^{HJDT} \leq 0.4^\circ C$.

6. Error caused by a switch $\Delta_{X}^{C}$. For high-quality measurement systems $\Delta_{X}^{C} \leq 0.03^\circ C$ for type K thermocouples [12].

9. Error caused by a switch $\Delta_{X}^{C}$. For high-quality measurement systems $\Delta_{X}^{C} \leq 0.1^\circ C$ for reference type S thermocouples and $\Delta_{X}^{C} \leq 0.03^\circ C$ for type K thermocouples [12].

Thus total error of the primary verification $\Delta_{X}^{PT}$ of a TBS with CPTF can be defined as (9):

7. Error caused by TBS with CPTF temperature field profile nonideality $\Delta_{X}^{F}$. This error is estimated below.

A periodic verification reference device is the zones $I_0 \cdots I_1$ of MTC. Deviations of their CC from the nominal one are fixed in the first verification. Thus the error $\Delta_{R}^{PT}$ will be defined by a zone $I_0 \cdots I_1$ CC drift during operating time. Drift $\Delta_{X}^{ED}$ doesn’t exceed 24.5 °C for operating time $\tau_E = 8000$ hours at operating temperature $T_{E} = 800^\circ C$ for type K thermocouples [3].

Let’s suppose: (i) time of verification doesn’t exceed $\tau_{ST} = 0.5$ an hour (ii) self verification is provided once a week. During the one year operating time total time of zones $I_0 \cdots I_1$ of MTC operation will not exceed $\tau_{ER} = 26$ hour. For type K thermocouples drift of the first 100 hour of operation equals to approximately half of the drift one year operation drift [3]. That’s why it is reasonable to prepare MTC before the primary verification. This preparation consists of operating of MTC in temperature field that “cover” future profile of the primary verification’s temperature field during 100...150 hours. Then $\Delta_{X}^{PT}$ will correspond to approximately 50 % of the maximum type K thermocouple drift during the time $\tau_{ER} = 26$ hour, divided by $\tau_{E} = 8000$ hour. Thus $\Delta_{R}^{PT} = (\tau_{ST} \cdot \tau_{ER} \cdot \Delta_{X}^{ED}) / \tau_{E} \leq 0.04^\circ C$.

Error due to nonideal TBS with CPTF profile of temperature field $\Delta_{X}^{F}$ is defined by the profile of temperature field set $\Delta_{X}^{FS}$ (relatively to temperature field of TBS with CPTF during the primary verification) and error due to control $\Delta_{X}^{FC}$. The error $\Delta_{X}^{FS}$ is defined by the control systems of TBS with CPTF additional thermocouples CC drift during operating time (their initial deviations of CC from nominal are taken into account in the primary verification of the TC). This error for used type K
additional thermocouples \( A_{X}^{FS} \leq 24.5 \, ^\circ\text{C} \) [3]. The error due to control \( \Delta_{X}^{FC} \) doesn’t exceed 1.2°C [14]. So, in this case \( \Delta_{X}^{PT} \) doesn’t exceed \( A_{X}^{PT} = \sqrt{A_{X}^{FS}^{2} + A_{X}^{FC}^{2}} \approx 25 \, ^\circ\text{C} \). However \( \Delta_{X}^{PT} \) doesn’t affect the verification error directly. It calls another error. The MTC total e.m.f. involves the e.m.f. generated by \( I_{1} \cdots I_{4} \) zones in primary as well as periodical verification. Just the individual deviations of the MTC CC from nominal can affect on the verification error of the zones \( I_{1} \cdots I_{2} \). They are taken into account at the primary verification. The zones \( I_{1} \cdots I_{2} \) are not operated in high temperature. Hence their error is neglectible small. Effect of \( I_{1} \cdots I_{4} \) zones is much greater. Their individual deviations of CC from nominal are taken into account at the primary verification. But they are operated at high temperature. That’s why the zones \( I_{1} \cdots I_{4} \) CC drift affects on periodical verification. Equivalent effect \( \Delta_{X}^{EO} \) on the total MTC e.m.f. equals to \( \Delta_{X}^{EO} = A_{X}^{FS} \cdot A_{X}^{PT} / T_{E} \leq 0.75 \, ^\circ\text{C} \) if temperature field deviates on \( A_{X}^{PT} \leq 25 \, ^\circ\text{C} \).

Thus additional error \( \Delta_{X}^{PT} \) that appears at periodical verification of the MTC approximately equals to

\[
\Delta_{X}^{PT} = \sqrt{A_{X}^{PT}^{2} + A_{X}^{EO}^{2}} \leq 1.2 \, ^\circ\text{C} \quad (10)
\]

The total error of a periodical verification \( \Delta_{X}^{PT} \) equals to summation of the primary verification error \( \Delta_{X}^{PT} \) and the additional error of a periodical error \( \Delta_{X}^{PT} \). If the first rank reference thermocouple is used for primary verification

\[
\Delta_{X}^{PT} = \sqrt{\left( \Delta_{X}^{PT} \right)^{2} + \left( \Delta_{X}^{EO} \right)^{2}} \leq 1 \, ^\circ\text{C} \quad (11)
\]

The total error of primary verification \( \Delta_{X}^{PT} \), if the third rank reference thermocouple is used, equals to

\[
\Delta_{X}^{PT} = \sqrt{\left( \Delta_{X}^{PT} \right)^{2} + \left( \Delta_{X}^{EO} \right)^{2}} \leq 1.2 \, ^\circ\text{C} \quad (12)
\]

5. Conclusions

The proposed method of the main thermocouple of TBS with CPTF verification can be considered as quite prospective. Its advantages are: (i) possibility of the periodical TBS with CPTF verification on operation place without replacement of a sensor; (ii) periodical verification doesn’t require reference thermocouple or any other reference temperature sensor; (iii) the periodical verification error doesn’t exceed 1.2 °C. Thus it is reasonable to generate algorithm for design of such sensors for various use.

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