Evaluation of Error of Method of Thermocouple with Controlled Profile of Temperature Filed

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Abstract. *It was proposed to reduce the impact of error due to thermoelectric inhomogeneity of thermocouple electrodes using stabilization of the temperature field along the main thermocouple (that measures the temperature of an object) [1, 2].However, the error of method occurs. It is related to errors of the main thermocouple and a thermocouple from the subsystem of control of the temperature along the main thermocouple electrodes. This paper proposes a method for theoretical evaluation of error of method.*

Keywords: Thermocouple, Error Due to Inhomogeneity of Thermocouple, Thermocouple with Controlled Profile of Temperature Field, Measurement Error, Error of Method.

1. Introduction

During operation of thermocouples (TC) over time degradation processes take place in the electrodes under the influence of the operating temperature. The rate of the degradation processes depends on the temperature at which certain sections of TC electrodes operated. That is, thermoelectric inhomogeneity of TC electrodes increases over operating time. Thus, degradation processes lead to two types of interrelated temperature measurement errors [3]:
1. Error which depends on the change of conversion characteristic (CC) of TC in time (drift);
2. Error which depends on the change of the output thermo-emf when the profile of the temperature field along TC electrodes changes.

Attempts have been made to correct the errors of the first type by periodic verification of TC and their drift prediction [4, 5]. However, thermoelectric inhomogeneity doesn't allow getting high accuracy of temperature measurement in this way [6]. This led to the development of verification methods [5] or calibration [7] in situ as well as their combination. However, these methods work properly only at steady temperature field along TC thermoelectrodes. Therefore the study of error due to inhomogeneity of thermoelectrodes has been made [6].

2. Thermocouple with Controlled Profile of Temperature Field

To eliminate the changes of the thermo-emf of inhomogeneous TCs due to the change of temperature field profile along their electrodes, a new TC based sensor, thermocouple with controlled profile of temperature field (TCPTF), was proposed [1]. TCPTF contains several temperature control subsystems that are located along the main TC (MTC) to stabilize the temperature field. So inhomogeneity of MTC cannot manifest itself. Errors of temperature measurement of systems using TCPTF are discussed in detail in [2]. The purpose of this paper is to develop a method for evaluating the upper limit of error of method of TCPTF.

Just the first section of heater H1 of TCPTF and its main thermocouple are shown in Fig. 1. The source of error of method is the heat flux q from heater H1 to the measuring junction of MTC. To reduce the influence of the heat flux q, that is for MTC being able to measure the temperature of environment T_S, firstly, its measuring junction should be put to a relatively large distance L1 from the nearest heater H1 (the ratio of L1 to the thermowell diameter of MTC is greater than 10); and secondly, the temperature which heater H1 should support (its controlling subsystem setpoint) is set equal to the temperature of measuring junction of MTC. Therefore, ideally, the heat flux q, due to lack of temperature difference along the interval L1, is equal to zero and error of method is absent. But due to the dispersions in CC of thermocouples MTC and TC1 [8], temperature difference ΔT_{tcs} along the distance interval L1 is not equal to zero (in Fig. 1 the case with maximum error of method is shown). Therefore heat flux q and error of method occur. If MTC and TC1 are of the same type and their maximum permissible error (tolerance [8]) is ΔT_{tc} °C, then the temperature difference ΔT_{tcs}, which causes error of method along the distance L1 is $\Delta T_{tcs} = \sqrt{2} \times \Delta T_{tc}$ °C. Due to the heat exchange with the environment of the temperature T_s from the thermowell surface of MTC, which is shown in Fig. 1 to the right of heater H1, the temperature difference between the environment and the electrodes of the MTC along L changes according to the curve ΔT_{real}. Then the value ΔT_{lim} which corresponds to the value of coordinate L1 is equal to the maximum value of error of method of the proposed TCPTF that distorts reading of MTC.

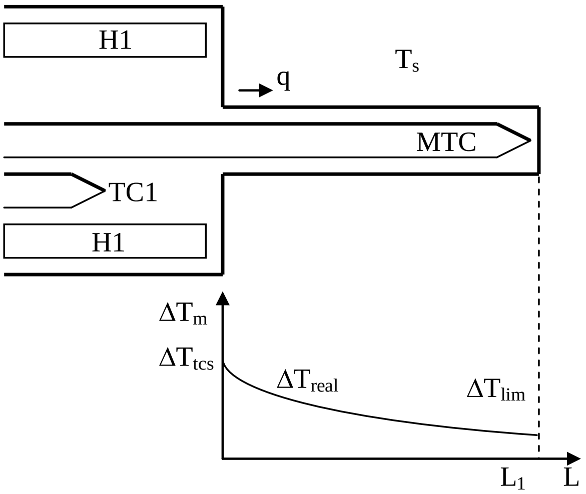

Fig. 1. Appearing of error of method of TCPTF and the plot of temperature changes along the MTC thermowell.

3. Analytical Determination of Error of Method

It is a very complex task to find ΔT_{lim} on the basis of static distribution of temperature. However, there is no need to calculate the whole curve ΔT_{real} (see Fig. 1) for determination of the limit of error of method ΔT_{lim}, as it is enough to find the change of temperature at the coordinate L1, which corresponds to the value of error of method ΔT_{lim}. Therefore, the method for evaluating ΔT_{lim} on the basis of its dynamic change of temperature difference ΔT_{tcs} has been developed.

We assume that at a certain moment the temperature difference between heater H1 and the measuring junction of the MTC is equal to zero. Subsequently, heater H1 abruptly increases this difference to the value of ΔT_{tcs} (see Fig. 1). In this case, there comes a transition process that can be described using Newton’s law of cooling [9]. Theoretically, this transition process continues indefinitely, but the limit of it, as time approaches infinity, can be evaluated. This limit will correspond to the error of method ΔT_{lim} caused by temperature difference ΔT_{tcs} between heater H1 and the measuring junction of the MTC.

To find error of method ΔT_{lim}, we write the heat balance equation for the thermowell of the MTC. The amount of heat flux q emitted by heater H1 during time dt is absorbed for changing the metal thermowell temperature on quantity dT as well as heat dissipation in environment with temperature T_S. According to Newton’s law [9], we write the differential equation for the steady state mode by determining the temperature of heating thermowell T as a function of time t:

$$qdt = cV\rho dT + \alpha S(T - T_S)dt \,, \tag{1}$$

where q - heat flux caused by temperature difference between heater H1 and the measuring junction of the MTC; c- specific heat capacity of thermowell material of the MTC; V- volume of the thermowell of the MTC; S - the area of external surface, which is in thermal contact with the environment, that is the area of thermowell of the MTC; α - heat transfer coefficient of steel to air; ρ - density of thermowell material of the MTC.

It should be noted that the Eq. 1 is written in case heater H1 is not on the side of the thermowell (as seen in Fig. 1), but it is located in its center. However, such an incorrect physical meaning of the Eq. 1 does not lead to a significant distortion of the result, if the heat flux q generated by H1 under the influence of ΔT_{tcs}, corresponds to the real one. Then the evaluation of error of method will be slightly overstated, with what we can reconcile. And, by the same token, the heat flux q can be calculated by the formula [9, 10]:

$$q = \frac{\lambda \Delta T_{tcs} S_N}{L} \quad , \tag{2}$$

where λ - thermal conductivity of the thermowell material of the MTC; ΔT_{tcs} - the temperature difference between heater H1 and the measuring junction of the MTC; S_N - the area of the surface through which heat flux is transmitted (cross-section area of the thermowell); L - distance from heater H1 to the measuring junction of the MTC.

Solving the Eq. 1 with respect to time t, we obtain the temperature dependence of the measuring junction of the MTC on time.

$$T = T_S + \frac{q}{\alpha S}\left(1 - e^{-\frac{\alpha S}{cV\rho}t}\right) \quad . \tag{3}$$

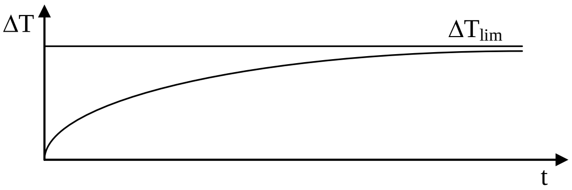

Fig. 2 The change of error of method ΔT_{lim} in time under the temperature jump of heater H1.

In Eq. 3, the term $\frac{q}{\alpha S}\left(1 - e^{-\frac{\alpha S}{cV\rho}t}\right)$ actually corresponds to the error of method ΔT_{lim}, and describes the change of error of method in time (see Fig. 2). If time t approaches infinity, then the term $e^{-\frac{\alpha S}{cV\rho}t}$ tends to zero. Thus, the upper limit of error of method ΔT_{lim} asymptotically approaches its limit

$$\Delta T_{lim} = \lim_{t\to\infty} \frac{q}{\alpha S}\left(1 - e^{-\frac{\alpha S}{cV\rho}t}\right) = \frac{q}{\alpha S} \quad . \tag{4}$$

4. Evaluation of Dependence of Error of Method on Measured Temperature

As can be seen from (1) ... (4), error of method ΔT_{lim} is a function of several variables. We evaluate its value for a specific pattern of TCPTF based on type K TC and has a body made of stainless steel [7]. For such a sensor

$S_N = 6{,}3\times10^{-5}\,m^2$; $L = 0{,}15\,m$; $S = 5{,}5\times10^{-3}\,m^2$; $\alpha = 44\frac{W}{m^2\times K}$; $\lambda = 14{,}2\frac{W}{m\times K}$ [10].

The permissible deviation of CC of TC from the nominal one depends on the measured temperature T_s. According to [8], the maximum permissible deviation of actual CC from the nominal one ΔT_{tc} for the type K TC is ±2,5°C for temperature interval 40 - 333°C and $\Delta T_{tc} = \pm 0{,}0075|T|$ for temperature interval 333 - 1200°C. The values ΔT are put into (2).

Calculation results of evaluation of the upper limit of error of method ΔTlim are shown on the graph in Fig. 3. As can be seen from the graph, ΔT_{lim} is a function of the maximum error of TC ΔT_{tc}. The upper limit of ΔT_{lim} increases linearly at temperatures over 333ºC. At lower temperatures, the upper limit of error of method ΔT_{lim} remains constant, as for type K TC in this range the maximum permissible deviation of CC from the nominal one ΔT_{tc} does not change.

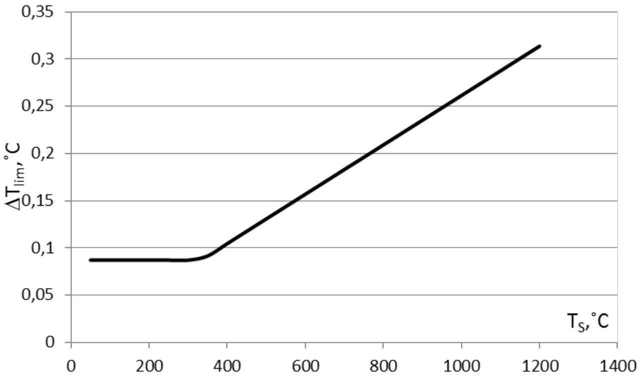

Fig. 3 Dependence of error of method ΔTlim on measured temperature Ts.

5. Conclusions

The proposed method for evaluation of error of method of TCPTF [2] is quite correct in terms of physics and quite simple. It provides a numerical evaluation of its upper limit. According to Fig. 3, the upper limit of the error of method of the proposed TCPTF is ten times smaller than the maximum deviation of CC of TC from the nominal one [8].

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References

[1] Kochan O., Kochan R. Thermoelectric transducer. Ukraine Patent № 97464. G01K 7/02.

[2] Kochan O., Kochan R., Bojko O., Chyrka M. Temperature measurement system based on thermocouple with controlled temperature field. Proceedings of the 4-th IEEE international workshop on Intelligent Data Acquisition and Advancing Computing Systems (IDAACS’2007), 2007, 47-51.

[3] Su Jun, Kochan O. The mechanism of the occurrence of acquired thermoelectric inhomogeneity of thermocouples and its effect on the result of temperature measurement. *Measurement Techniques*, 57 (10): 1160–1166, 2014.

[4] Su Jun, Kochan O. Investigations of thermocouple drift irregularity impact on error of their inhomogeneity correction. *Measurement science review*, 14 (1): 29-34, 2014.

[5] Kortvelyessy L. Thermoelement Praxis. Vulkan-Verlag, Essen, 1981. (in German)

[6] Holmsten M.,·Ivarsson J., Falk R., Lidbeck M., Josefson L.-E. Inhomogeneity measurements of long thermocouples using a short movable heating zone. *International Journal of Thermophysics*, 29 (3): 915-925, 2008.

[7] Hundves A., Buschfort H. Self calibrating temperature sensing probe and probe – indicator combination-United State Patent 3.499.340. 73-1, G01 -15/00.

[8] International Standard IEC 584-2. Part 2: Tolerances.

[9] Lienhard J. IV, Lienhard J. V. A Heat Transfer Textbook, Phlogiston Press, Cambridge, 2008.

[10] Kuchling H. Taschenbuch der Physik, VEB Fachbuchferlag, Leipzig, 1980.