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Decreasing of Thermocouple Inhomogeneity Impact on Temperature Measurement Error

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Abstract: One of the most effective methods of reducing the impact of error from acquired thermoelectric inhomogeneity of thermocouples' electrodes is discussed in this article. The method consists in stabilizing the profile of the temperature field along the main thermocouple electrodes (which measure the temperature of the object). There is also discussed the design of device for profile stabilization of the temperature field and methods for control this profile. *Copyright © 2013 IFSA.*

Keywords: Thermocouples, Inhomogeneity, Neural networks, Thermocouple with controlled profile of temperature field.

1. Introduction

When measuring temperatures above 600 ºC thermocouples are the most common sensors although they have several disadvantages. In particular, they have too big error for many technological processes [1]. It is ten times bigger than the error of the best measurement channels [2].

The basic measurement errors of the thermocouples are:

1. Large initial deviation of conversion characteristic (CC) from the nominal for common type K thermocouples to 5.5 °C at 600 °C and to 8 °C at 1100 °C [1];
2. Significant drift of CC during prolonged operation at high temperatures (CC of thermocouples change while operating time) – for type K thermocouple during 1000 hours of operating time up to 0.5 °C at 600 °C and 10 °C at 1100 °C [3, 4];
3. Error from acquired during prolonged operation at high temperatures of thermoelectric inhomogeneity of the electrodes [5, 6] – for type K thermocouple during 1000 hours of operating time reaches up to 10 °C at 1100 °C [7].

The cause of error from the acquired inhomogeneity of thermocouple electrodes is related to the dependence of degradation from temperature of operation. During prolonged operation each segment individually acquires its CC. If you change the profile of the temperature field along the thermocouple electrodes the temperature of their segments change correspondingly to their position and respectively the error of each segment varies, which means that the overall thermocouple error changes despite the fact that the temperatures of the measuring and reference

junctions remain constant. Acquired inhomogeneity is considered to be the main reason of error as it is stated in [5-7] and in [8] it is concluded that the error of the thermocouple which has been in use cannot be at all corrected although recent studies indicate that it is possible to reduce the impact of the inhomogeneity error on temperature measurement using a thermocouple [9, 10]. Let us consider one of the most effective methods [10].

2. Method for Improving the Accuracy of Measurement of Temperature Using Inhomogeneous Thermocouples

As it was mentioned above, the error of the acquired inhomogeneity manifests itself after changing the profile of the temperature field along the thermocouple electrodes. The basic idea of the method presented in [10] is as follows. If you do not allow the change of the temperature field profile (or stabilize it) the inhomogeneity error cannot show itself. It is possible not to allow this change by means of creating for the thermocouple electrodes a virtual profile of the temperature field with the help of additional temperature control systems. The heaters and sensors of these systems should be arranged along the axis of the thermocouple electrodes.

Design concept of the proposed thermocouple with controlled profile of temperature field (TCPTF) is represented in Fig. 1 [10, 11]. The main thermocouple MTC measures the temperature of the object. There are placed temperature field control zones along its electrodes. They consist of heaters H1 ... Hn and the corresponding temperature sensors TC1 ... TCn. Available junctions of all thermocouples are connected to measuring and control system (not shown in Fig. 1).

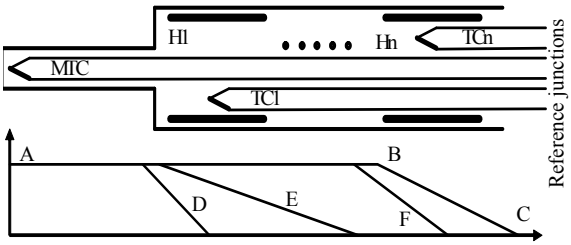

Fig. 1. Design concept of the proposed thermocouple with controlled profile temperature field.

The temperature field profile ABC is shown at the bottom of Fig. 1, it is set by means of temperature controllers based on TC1, H1 ... TCn, Hn. While changing the temperature field profile of the object within the limits specified with profiles D ... F ABC profile will not change and therefore the error of the acquired inhomogeneity of MTC cannot show itself.

The measuring and control system for TCPTF must ensure uniform measurement error of the thermo-emf for thermocouples TC1…TCn. For this reason this system works best if it is not used as a multi-channel (each thermocouple has a separate measuring channel) but as a multipoint (the measuring channel is one for all and switch alternately relays it to separate thermocouples) [12]. As it is argued in [11] the error caused by the acquired inhomogeneity of the MTC electrodes (temperature field profile change along its electrodes) does not exceed 0.13 °C, therefore, it can be neglected, whereas the total error of temperature measurement using TCPTF (in case of error correction of the initial deviation from the nominal CC of the MTC and its drift of CC during operation based on calibration using reference thermocouple) does not exceed 1.4 °C.

3. Furnace for TCPTF Temperature Field Profile Control

Shown in Fig. 1 and in [10, 11] design of the TCPTF produced as a single integrated sensor has significant drawbacks:

1. Complexity of the design;
2. Lack of unification with existing types of thermocouples;
3. Complexity of change of MTC when it has significant degradation of electrodes;
4. Need for metrological certification as new type sensor.

These drawbacks are significant; they hinder the possibility of widespread use of TCPTF. Simultaneously, these drawbacks are not inherent to the proposed method of reducing the impact of changes in the temperature field on the measurement error. They are the result of the implementation of the TCPTF as an integrated sensor. To eliminate these problems TCPTF should be divided to: (i) the sensor itself i.e. MTC (standardized thermocouple being produced), (ii) means of stabilizing the profile of the temperature field along the MTC's electrodes (special furnace). Then all the above disadvantages are eliminated.

Design concept of the proposed special furnace is shown in Fig. 2.

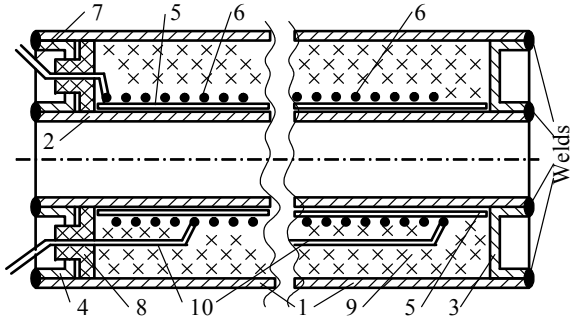

Fig. 2. Design concept of a special furnace.

It consists of outer 1 and inner 2 tubular shells (diameter of the inner shell 2 corresponds to the outer diameter of the standardized thermocouple). Shells 1 and 2 are connected with walls 3 and 4 by the welding procedure. The insulation (ceramic) cylinder 5 is placed inside the furnace. Heater 6 is wounded (or sprayed) on the cylinder 5. Lead-outs 7 of the heater 6 pass out through the insulating sleeve 8. The space between shells 1 and 2 is filled with insulating material 9.

The main requirement for the design was to reduce the number of lead-outs that are linked to the front wall of the furnace (left in Fig. 2; the right wall is at high temperature). That is why the heaters H1 ... Hn and their temperature sensors TC1 ... TCn are combined. These heaters 6 are wounded (or sprayed) with the material of one thermocouple electrode (e.g. chromel). Lead-outs 10 of heaters 6 are made of material of other thermocouple electrode (e.g. alumel). When manufacturing heaters separately the heaters H1 ... Hn and sensors TC1 ... TCn will have lead-outs for n heaters even to 4 n (n – number of heaters).When they are combined the number of lead-outs will be n +1.

4. Methods of Temperature Field Profile Control

It should be noted that between the various heaters H1 ... Hn (and their sensors) there is a significant thermal bond. Therefore, when using conventional multichannel controllers there is a great possibility of losing the stability (generation of temperature fluctuations). Multi-zone control systems, which provide stability when there is the mutual influence of certain areas, require significant computational resources. In [13] there is proposed a simple method of control that can be implemented with 8-bit microcontroller. It is based on two statements:

1. Dependence on the temperature increments from the increments of power is linear;
2. In computing the increases the powers sum not heat flows but temperatures directly.

Such statements contradict thermodynamics. However, they allow you approximately calculate the required power changes of heaters for small deviations of the temperature field profile from the preset field. It is necessary to solve (e.g. with Gauss method) such a system of equations as

$$\begin{cases} \Delta T_1 = k_{11}\Delta P_1 + k_{12}\Delta P_2 + ... + k_{1n}\Delta P_n \\ ..... \\ \Delta T_n = k_{n1}\Delta P_1 + k_{n2}\Delta P_2 + ... + k_{nn}\Delta P_n \end{cases}, \quad (1)$$

where $\Delta T_1 \ldots \Delta T_n$ are the necessary changes in temperature of the zones heaters from 1 to n; $\Delta P_1 \ldots \Delta P_n$ are the necessary changes in power of the corresponding heaters; $k_{11} \ldots k_{nn}$ are the effect coefficients of individual heaters on the temperature in zones.

After calculations and change of power of the heaters the end of transitional heat exchange should be ensured. The next change of power of the heaters (based on the new temperature measurement result in all zones) may be performed after a delay of at least three time constants of the furnace. Thus, we get a practically open regulatory system that does not lose stability (it is not prone to self-excitation).

However, the described method of regulation works just with small and slow changes in the profile of the temperature field. Coefficients $k_{11} ... k_{nn}$ must be defined for each operating temperature of each zone. But even then the installation of the preset temperature field profile requires several cycles of refinement of the heaters' power.

Neural network (NN) method can be used to improve the accuracy of the required change of the heaters' power at different temperatures. The basic idea of the method is to establish control of the NN trained under various changes in the profile of the temperature field MTC and operating of TCPTF at different temperatures. Number of outputs of NN equals to the number of heater zones. The proposed structure of the temperature field control system of MTC is presented in Fig. 3. It consists of TCPTF (in Fig. 3 presents a set of sensors S and heaters H), a multichannel measurement subsystem MMS. It also contains multi-block units: (i) furnace temperature set unit (TSU); (ii) subtract unit SU; (iii) control unit CU. Inputs of the NN get information about temperature differences from SU and values of current temperature of each zone from MMS. Thus NN has information about the desired change in the temperature of each zone and the information about the temperature of each zone. It allows NN to take into account the dependence of thermal processes on temperature. Thus NN can control the CU properly. CU provides any changes only after the end of the transition process of temperature setting for all zones (same as in the previous method to avoid self-excitation).

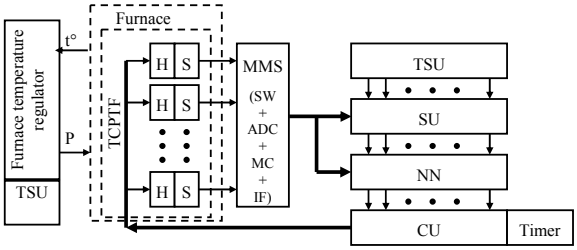

Fig. 3. Block diagram of the measurement and control system in the maintenance mode profile of the temperature field.

Neural controllers are usually trained using an appropriate model of control object or when they linked in parallel to the control object ("teacher"). The first method requires an adequate model of

control object, which has high accuracy; its errors should be several times smaller than the allowable control errors. Parameter identification of high-precision models of multi-zone control objects is a difficult task that requires a significant amount of experimental research. Method "with a teacher" requires the use of regulators, which already provide appropriate control of the temperature profile fields of the TCPTF, i.e. can solve the problem in advance.

It is proposed to train NN on site of operation not to use the object model and TCPTF. To do this, while training the structure of the system is changed according to Fig. 4. Inputs of CU are connected to the power set unit PSU and outputs NN are connected to training unit TU of NN. During the training PSU gives a signal for TSU to remember the current temperature and forms for CU random (positive or negative) changes of power of heaters H. After heating or cooling zones MMS measures temperatures and delivers it to the MU and NN. The trained NN would generate power changes, which would return the temperature of zones to the initial value (correspond changes formed with CU). If the changes are not equal to preset with PSU, then TU alters neuronal weights and shifts of NN to come closer to changes formed with PSU. The method requires 25-30 test power changes at different temperatures, and then NN can learn from those experimental data.

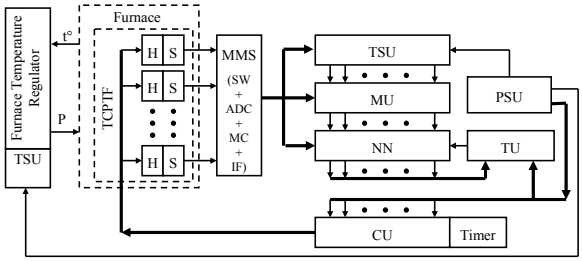

Fig. 4. Block diagram of the measurement and control system using neural network training.

The proposed training method doesn't require measured object's mathematical models due to coincidence of its experimental research and training of NN. That's why trained NN is adequate to an object but not to its mathematical model. Transition to new heaters' power occurs synchronously for all zones. This transition becomes just if the heat (cool) transition process of all zones ended completely (the same as in [13]). That's why the control system remains open. The proposed method remains robust to generation of temperature waves.

Computational complexity of the proposed method isn't higher than computational complexity of the method proposed in [13]. Total amount of NN outputs computations approximately equals to total amount of computations for system of linear equations solving. But NN during training generalizes data about TCPTF parameters dependence on separate zones temperature. This fact allows to take into account nonlinearity of TCPTF as a controlled object. This nonlinearity is caused by heat capacity and heat conductivity of TCPTF dependence on temperature.

5. Conclusions

The proposed solution allows considerable improvement of temperature measurement precision for thermocouples with significant inhomogeneity of electrodes acquired during operation. All known methods for thermocouples errors correction [3, 10] can be applied for accuracy improvement. The proposed design of furnace allows to use standardized thermocouples. It simplifies design of TCPTF given in [10, 11] and eases its application in practice. The proposed NN method of furnace heaters' power control has low computational complexity. But it allows to fix even considerable difference between preset and current temperature fields in one or two iterations.

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