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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 due to acquired thermoelectric inhomogeneity of thermocouples' electrodes is discussed in this article. The method consists in stabilizing the profile of the temperature field along electrodes of the main thermocouple (which measures 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.

I. Introduction

Recently there are many temperature sensors, based on various physical phenomena, occur in practice [1, 2]. But thermocouples are the most common sensors for temperature measurements above 600 ºC although they have several disadvantages. In particular, they have too big error [3] for many technological processes. It is ten times bigger than the error of measurement channels [4].

The basic measurement errors of the thermocouples are:

1. large initial deviation of conversion characteristic (CC) from the nominal CC. For the most common type K thermocouples these deviations may be up to 5,5 °C at 600 °C and to 8 °C at 1100 °C [3];
2. significant drift of CC during prolonged operation at high temperatures (CC of thermocouples changes while operating time) — for type K thermocouples during 1000 hours of operating time up to 0,5 °C at 600 °C and 10 °C at 1100 °C [5, 6];
3. error due to thermoelectric inhomogeneity of the electrodes, acquired during prolonged operation at high temperatures [7, 8]. For type K thermocouples during 1000 hours of operating time it reaches up to 10 °C at 1100 °C [9].

The cause of error due to acquired inhomogeneity of thermocouple electrodes is related to the dependence of degradation from temperature of operation. During prolonged operation each segment of electrode changes its CC according to its temperature of operation. If you change the profile of the temperature field along the thermocouple electrodes the temperature of their segments change correspondingly to their position. Respectively the error of each segment varies, so 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 [7-9]. It is concluded that the error of the thermocouples which have been in use cannot be at all corrected [10]. But recent studies indicate that it is possible to reduce the impact of the error due to inhomogeneity on temperature measurement using a thermocouple [11, 12]. Let us consider one of the most effective methods [13].

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

As it was mentioned above, the error due to acquired inhomogeneity manifests itself after changing the profile of the temperature field along the thermocouple electrodes. The basic idea of the method presented in [12] is as follows. If you do not allow the change of the temperature field (stabilize it) the error due to inhomogeneity cannot show itself. One can stabilize the temperature field by means of creating for the thermocouple electrodes their own profile of the temperature field using additional temperature control systems. The heaters and sensors of these systems should be arranged along the thermocouple electrodes.

The pattern of the proposed thermocouple with controlled profile of temperature field (TCPTF) is given in Fig. 1 [12, 13]. The main thermocouple MTC measures the temperature of the object. There are placed temperature field control sections along its electrodes. These sections consist of heaters H1 ... Hn and the corresponding temperature sensors TC1 ... TCn. Reference junctions of all thermocouples are connected to measuring and control system (it doesn't shown in Fig. 1).

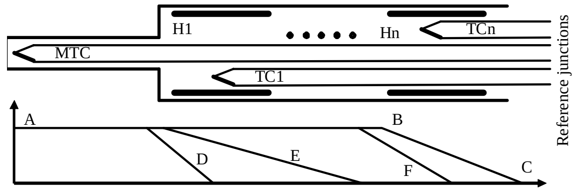

Figure 1. The pattern of the proposed thermocouple with controlled profile temperature field.

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. If the temperature field profile of the object changes within the limits specified with profiles D ... F, the profile ABC will not change and therefore the error due to acquired inhomogeneity of MTC cannot show itself.

The measuring and control system of TCPTF must ensure high accuracy of measurements 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 each thermocouple is switched to it alternately by relays) [14]. As it is argued in [13] the error due to acquired inhomogeneity of the MTC electrodes (temperature field profile changes along its electrodes) does not exceed 0,13°C, therefore, it can be neglected.

The total error of temperature measurement using TCPTF does not exceed 1,4°C. To achieve such accuracy for errors correction of the initial deviation from the nominal CC of the MTC and its drift of CC during operation it is necessary to use a reference thermocouple of error no more than 0,6°C.

III. Furnace for TCPTF's Temperature Field Profile Control

Shown in Fig. 1 and in [12, 13] pattern 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 of 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.

Pattern of the proposed special furnace is shown in Fig. 2. 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 between the shell 2 and heater 6. 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 sleeve 8 has mushroom looking shape to better fixation. The space between shells 1 and 2 is filled with thermal insulating material 9.

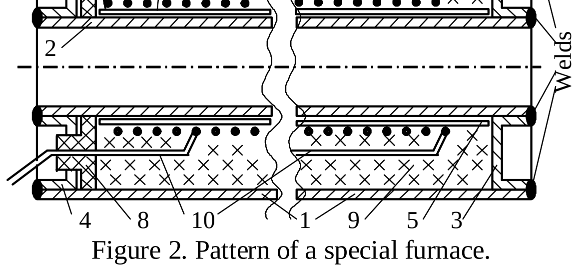

Figure 2. Pattern of a special furnace.

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). So each heater with its lead-out makes a thermocouple which can measure temperature in the edge of a zone. Temperature in the center of the zone can be approximately calculated as the average temperature of temperatures at the edges of this and previous zones.

Such superposition allows us to reduce required number of lead-outs. When manufacturing heaters and sensors separately, the heaters H1 ... Hn and sensors TC1 ... TCn will have lead-outs for n heaters equal to 4n (n – number of heaters). When they are combined the number of lead-outs will be only n +1.

IV. 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 [15] there is proposed a simple method of control that can be implemented using 8-bit microcontroller. It is based on two statements:

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

Such statements contradict thermodynamics. However, these statements allow you to calculate the required power changes of heaters approximately for small deviations of the temperature field profile from the preset one. It is necessary to solve (e.g. with Gauss method) a system of equations below [15]

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

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 power of the heaters the end of transitional heat exchange should be ensured. The next power change of the heaters (based on the new temperature measurement results 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 $k_{11} \ldots k_{nn}$ 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 the number of heater zones. Number of inputs is two times as big as a number of outputs, in order to take into account required temperature changes and corresponding temperatures for each zone.

The proposed structure of the temperature field control system of MTC is presented in Fig. 3. It consists of TCPTF (in Fig. 3 presented as a set of sensors S and heaters H), a multichannel measurement subsystem MMS, furnace temperature set unit TSU, subtract unit SU and control unit CU. TCPTF is located in the thermal unit which is controlled by TUC. MMS consists of a switchboard SW, an analog to digital converter ADC, a microcontroller MC and an interface unit IF.

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 current temperature of each zone. It allows NN to take into account the dependence of thermal parameters 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 (in the same way as in the previous method to avoid self-excitation).

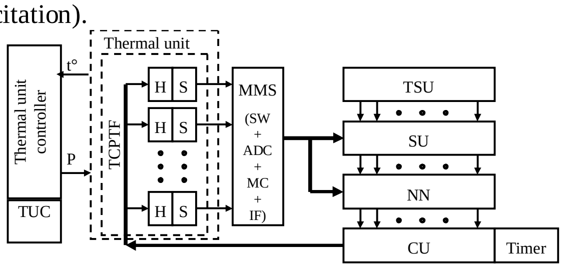

Figure 3. Block diagram of the measurement and control system in the maintenance mode of profile of temperature field.

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 without use any models. 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 SU and NN. The trained NN would generate power changes, which would return the temperature of zones to the initial value (correspond changes formed with PSU). 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 (without changes of power of heaters in reality).

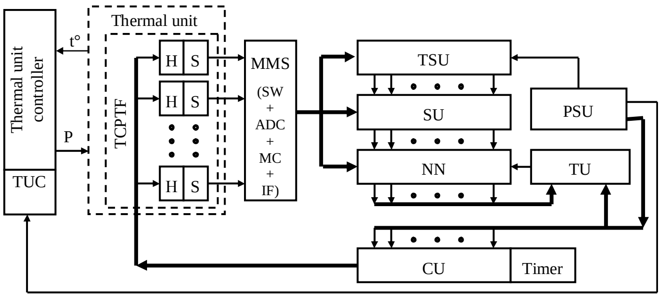

Figure 4. Block diagram of the measurement and control system using neural network training.

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 [15]). That's why the control system remains open. The proposed method remains robust to generation of temperature waves.

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.

Computational complexity of the proposed method isn't higher than computational complexity of the method proposed in [15]. 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 us 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.

V. Experimental results

For the experimental studies of the first temperature field setting method (based on the solution of equation (1)) it is necessary first to determine the coefficients $k_{11}...k_{nn}$. For their direct determination by experimentation is necessary to make the system of equations k_{nn}^2 and solve it relatively to $k_{11}...k_{nn}$. There is no problem solving it. But assembling such a system there should be obtained the experimental data for n^2 temperature field profiles. This method is very time-consuming and laborious. It also has a low accuracy - with so many temperature field profiles differences between them will be small. Then the measurement errors and not ended transient processes will considerably influence on coefficients $k_{11}...k_{nn}$ calculation.

The method of determining individual coefficients for each heater is suggested. Thus every time you start the experiment only one of the heaters (for example, j) is turned on. In this case the system of equations (1) is reduced to column. Solving it allows getting the coefficients $k_{j1}...k_{jn}$. The results of each of these experiments can be represented as a graph (Fig. 5). Using such a graph it is possible to find the coefficients $k_{j1}...k_{jn}$ directly from it. Thus it is enough to carry on n experiments for n heaters.

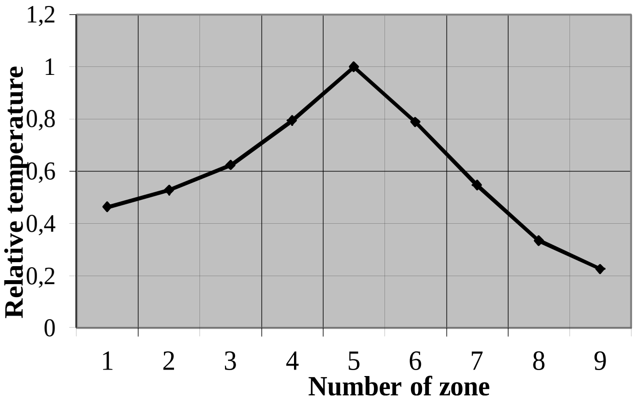

Figure 5. The relative distribution of temperature change along the thermocouple with controlled temperature field profile when one heater is turned on.

The suggested method of determining the coefficients $k_{11}...k_{nn}$ assumes that all heaters powers are equal by default. However, the real powers of the heaters of individual zones are not the same. To take into account the difference between the powers of heaters let's represent the power increases/decreases $\Delta P_1 ...\Delta P_n$ of the heaters in each term of the right side of (1) as

$$\Delta P_i = \Delta P_{MIN} \cdot k_i^P \qquad (2)$$

where k_i^P is the coefficient of the excess of individual heater power over the power of the heater making minimum temperature in its zone during the experimental determination of coefficients $k_{11}...k_{nn}$. In its turn the additional coefficients $k_1^P ...k_n^P$ can be defined as

$$k_i^P = \Delta T_i / \Delta T_{MIN} \qquad (3)$$

where ΔT_{MIN} is the minimum temperature change of the zone with its heater during the coefficients determination $k_{11}...k_{nn}$; ΔT_i is the temperature change with its $i-th$ heater.

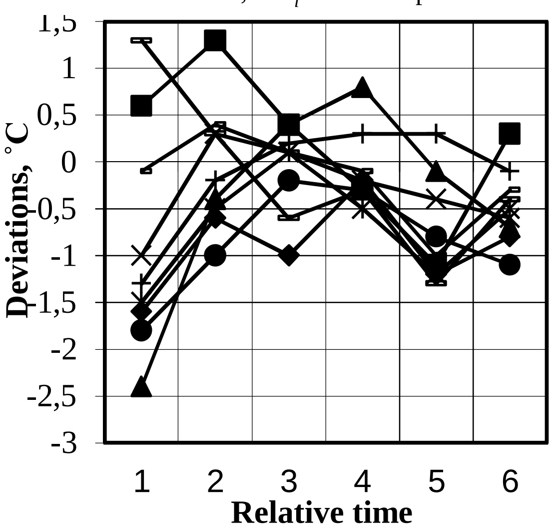

Figure 6. The process of setting the temperature field profile using the method based on solving a system of linear equations

The results of experimental studies of the setting of the temperature field profile with the method based on solving a system of linear equations (1) is shown in Fig. 6. Time units on the x-axis are the relative unit value of which correspond to the dual time constant of TC with CPTF. As shown in Fig. 6, the deviation of the temperatures of zones of the TC with CPTF from the set ones gradually decrease. However, the duration of the setting of the temperature field profile is large. Even with small deviations (in Fig. 6 - less than 2.5 ° C) it requires a quite large number of iterations.

In Fig. 7 there are shown similar graphs for the method of control using neural network. As shown in Fig. 7, setting the profile of a given temperature field requires only two time constants (one iteration cycle). This also applies to large (up to 20 ° C) temperature field profile deviations from the specified values.

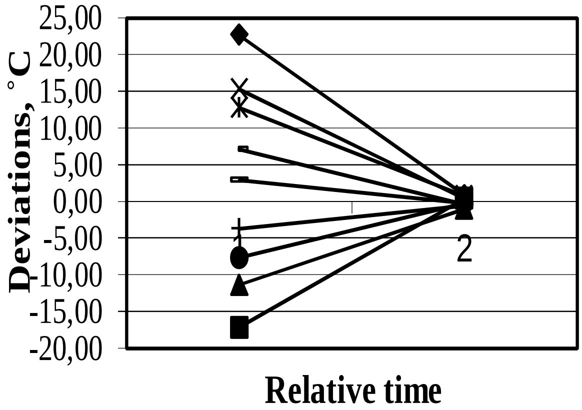

Figure 7. The process of setting the temperature field profile using the control method based on neural network

CONCLUSIONS

Proposed in this paper method to reduce the influence of thermoelectric inhomogeneity of thermocouples, acquired during long-term operation on the temperature measurement error, is very effective. The stabilization of the temperature field profile almost eliminates the effects of changes of temperature field profile of the object on the thermo-emf of the thermocouple that measures object's temperature. The proposed solution is not complex.

One of the problems is the method of control heaters during stabilizing the temperature field profile. This is due to the necessity of exclusion the self-excitation mode. Proposed solution allows solving this problem even when 8-bit microcontrollers are used to calculate the required power increases/decreases of the heaters. Although in this case, before the operation, a PC is required for the adjustment of the control subsystem and neural network training.

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