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Investigation of Thermocouple's Drift Speed Influence on Error of their Heterogeneity Correction

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Abstract: The method of an error correction acquired during a long term exploitation of the thermocouple electrodes heterogeneity has been studied in this paper. It is based on testing the results of different temperature fields, while thermocouple error is considered as the distribution between thermocouple's electrode zones, received using neural network learned on calibration results. These mentioned zones of thermocouple are virtual. There was a residual error in considered method that uses three-layer perceptron to evaluate error split. It is shown that the 4 times reduction of the possible number of temperature field profile (compared to the amount of thermo electrodes' virtual zones) leads to the increase of the error from 2 % to 5 %. Even such a result is acceptable. While standard deviation reaches ±0.45 °C. *Copyright © 2013 IFSA.*

Keywords: Neural networks, Error of thermocouples, Inhomogeneity of thermocouples.

1. Introduction

Despite the appearance of a large number of temperature measuring sensors and detectors – optical, laser, thermo-noise ones that have appeared recently to measure the temperature in the ranges above 500 °C, the industry is using traditional thermoelectric converters based on thermocouples. Regardless of high accuracy of modern devices [1, 2], as well as a large number of scientific papers writing about the increase of thermocouples accuracy [3-10], the temperature measurement error hasn't decreased essentially over the last decade. It is caused by the fact that the measuring channel has its own thermocouple error, which basically hasn't changed. Therefore, the way to increase the temperature measurement accuracy, that involves the error correction of existing thermocouples, with the exception of perfect thermocouple creation, is still an actual task.

The methods of error correction based on: (i) thermocouple initial distribution of the conversion functions (CF); (ii) time drift of the CF under the influence of temperature exploitation; (iii) improvement of the time drift's individual prediction within the interval between the measurements or calibrations [10-11]; can significantly improve the accuracy of the thermocouple temperature measurement. However, these methods do not take into consideration thermocouple errors caused by acquired during continuous exploitation thermoelectric heterogeneity of the electrodes. This error appears as the dependence on generated by thermocouple (which has long exploitation period) thermo-electromotive force existing not only between the temperatures of

the working and free ends, but also between temperature profile fields along thermocouple electrodes [12-16].

The error creation process obtained during a continuous exploitation of the electrode thermoelectric heterogeneity in the thermocouple is explained on the Fig. 1 On the Fig. 1(a) a thermocouple (TC) (thermoelectrodes chromel and alumel, type K) is represented while being exploited in the temperature field of the object, the profile of which is set by the ABCD line.

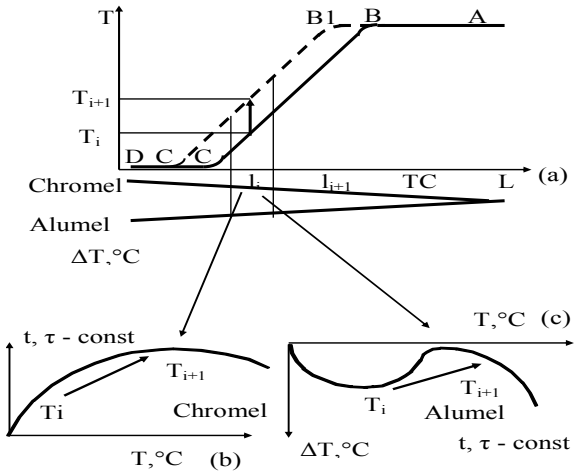

Fig. 1. Creation of an error obtained in a process of continuous exploitation of the thermoelectric irregularity in thermocouple electrodes.

Let us examine a certain section l_i of the thermocouple. Due to the fact that during the exploitation period τ thermoelectrodes degraded (components oxygenation, admixture diffusion, recrystallization, etc.), the CF of the l_i section deviates from the normal one. According to [17, 18], the time τ and temperature t that are equal to the temperature T_i of the l_i exploitation section and the ΔT of its CF taken from the nominal one can be graphically represented on the Fig. 1(b) and 1(c). Let us assume that as the result of the object's temperature field profile change in AB1C1D the l_i section has changed from the continuous exploitation temperature T_i into T_{i+1} temperature. Then the CF deviation of both thermo electrodes on the section l_i will change from the nominal one. In both cases this deviation from the characteristic of the T_i temperature will become the one that is characteristic of the T_{i+1} temperature, (see the Fig. 1(b) and Fig. 1(c); changes of the CF errors deviation are shown by the arrows). The same process of the CF error change from the nominal one will take place in all the other sectors of both thermo electrodes. As the result generated by thermocouple thermo-electromotive force will change avoiding the fact that according to the Fig. 1(a) the temperature of a free end and the one that is being used will remain invariable and the temperature measurement error will appear caused by the thermoelectric heterogeneity of thermocouple thermoelectrodes.

This property of the thermocouples that had been exploited for quite a long time led to the made in [12-14] conclusion that thermocouple errors cannot be adjusted. The attempts to reduce the errors from the obtained heterogeneity [19, 20] brought us to the conclusion that the correction of the drift should be made for each sector separately using the prognosis of their drifting. But to provide a sufficient precision of this kind for an individual prognosis it is necessary to correct it periodically using the results of the actual CF deviation from the nominal one. However, the inspection of the thermocouple or its calibrating allows obtaining only the sum of the CF deviations in all sectors while this sum should be divided among these sectors. In [20] it was proposed to use four possible empiric distributional criteria of the total error between separate sectors but those criteria were not proved experimentally and the wrong criteria might not only do not reduce the error from the heterogeneity but might also increase it due to the prognosis error rise.

The basis of the method that includes a substantial reduction of the error, obtained in the thermocouples heterogeneity exploitation process that influences the measurement result, is an investigation of its properties conducted in [20]. In [20, 21] it was proposed that error's correction method, which is based on the experimental research of the thermoelectric transformer's error, should be conducted during its periodical calibration in temperature fields of different profiles.

The aim of this article is to examine the non-excluded (residual, uncorrected) error of the deviation correction method from the obtained in the process of the exploitation of the thermocouple thermoelectric heterogeneity [20, 21], caused by the individual change of the CF drifting speed in certain electrode sectors.

2. Method of the Error Correction Obtained from the Thermoelectric Heterogeneity of the Thermocouple

Main idea of the proposed in [20, 21] method consists in the fact that if the prognosis of the total error of the drift defined during the thermocouple calibration and the CF are distributed between the sectors of its thermocouple accurately and conduct a correction of the individual mathematic models of the CF sectors drift then the prognosis of the thermocouple errors (both time drift and heterogeneity error) will have the same higher precision for the moment of current calibration as for

the future exploitation. The accuracy of the heterogeneity error for the current calibration moment may be checked straight away by changing the temperature field profile along electrodes of the thermocouple that is being checked. If the corrections calculated for all variants of the temperature field profile are close to the experimentally defined errors it is obvious that the distribution of the total error was conducted correctly.

The main drawback of the described method is a tremendous labor intensity of the periodical calibration. If the amount of sectors into which a thermocouple is divided is accepted as n, then in calculation of the individual errors of each sector by solving the range of equations the amount of temperature field profiles, where thermoelectric transformer should be calibrated, is $2n$ (for two thermoelectrodes). During this arises a contradiction. The criterion for thermoelectrodes division into sectors is a condition that in the sector's range drift is the same. That is why to increase the accuracy of the n prognosis it is necessary to augment. Then individual mathematical models of the drift sectors can describe the character of their CF drift more adequately. However, with the increase of n the amount of temperature field calibration profiles rises as well, i.e. it increases its work intensity.

In [20, 21], to reduce the work intensity of the method it is proposed to use generalizing qualities of the neural networks. Training of the heterogeneity for the neural network is formed in the following way: each vector is built on the basis of the thermoelectric transistor's calibration results conducted in one of the temperature field profiles.

To the input there are presented the neurons of the neural network current for the given temperature field profile values of the temperature on all sectors of the thermocouple (during this process it is necessary to maintain always the same accordance between sector's number and the input neuron's number). To the output there are presented the total error prediction result deviations in all sectors of the thermocouple from its actual error for the given of the temperature field profile (obtained as a result of the thermocouple's calibration).

Three-layer perceptron was selected as a neural network [22]. Its input neurons perform only the distributive functions. Their amount corresponds to the amount of the sectors, i.e. 24, into which both thermoelectrodes are divided.

Main generalizing properties belong to the neurons of the hidden layer. Their output signal h_m is defined by the product of added up weight multiplied by the activation function taking into consideration the displacement T_m

$$h_m = F(\sum_{i=1}^{g} w_{im} \times X_{im} - T_m), \quad (1)$$

where w_{im} is the weight coefficient i is the input of the m is the neuron; X_{im} is the value that is sent to the i is the input of the m is the neuron from the input neurons; $F(.)$ is the activation function, is the same to all neurons of the hidden layer.

As an activation function it is reasonable to use a sigmoid

$$F = \frac{1}{1+e^{-x}} \quad (2)$$

The amount of neurons in the hidden layer is selected experimentally but it should be considerably smaller than the half of the amount of the temperature fields profiles during which the testing was taking place, otherwise perceptron loses its generalizing properties (its tendency to transform into associative memory starts to be obvious). During the research it has became apparent that just three neurons of the hidden layer would suffice. Initial neuron is linear, i.e. its activation function equals one.

Artificial neural network is trained according to the *back propagation* algorithm using the Levenberg-Markuardt method. Maximum amount of the training epochs is 4000 (maximum training time – 4 minutes). In a training process, that takes place during several training cycles, weight w_{im} and the training replacement T_m factors adapt themselves to the hidden laws of drifting in the CF sectors of the thermoelectrodes and predict the deviation of the electromagnetic transformer in different temperature fields with a small error and high metric security. Values, received with the help of a trained neural network error prediction in the random temperature fields, are implemented to correct individual mathematical CF drift models of the thermocouple's sections.

3. Method of the Non-excluded Error Investigation of the Proposed Method

Experimental research of the proposed method does not allow sufficient exploration of its metrological characteristics. Specific implementations of the CF drift thermoelectric transformers obtained under conditions of one or several experimental boards are substantially limited and do not exhaust their possible exploitation conditions. Analytical investigations of the proposed method's error require the creation of mathematical model drift system of the electrodes' CF sectors which can correspond to the possible variants of the thermoelectric transformers' exploitation conditions. That is why an optimal method for the metrological research of the proposed method characteristics is an imitational modeling.

The estimations of the thermocouples errors in different profiles of the temperature field, which were presented in [23], are base of training sets. These estimations are based on the approximation of experimental research data [17].

Received in [23] values of the error from the obtained in the process of exploitation during 1000 hours thermoelectric heterogeneities of the XA type thermocouple electrodes when the diameter of the electrodes is 1,2 mm correspond to the calibration in 46 profiles of the temperature field concerning the initial temperature profile of the exploitation field. To conduct an experiment, values of the error, received from the obtained thermoelectric heterogeneity with the change of the thermocouple electrodes submersion depth, were selected, i.e. in the process of exploitation in the most dangerous mode taking into consideration the appearance of an error from the obtained thermoelectric heterogeneity [23].

Maximum training selection, which according to [23] imitates the results of heterogeneous thermocouple calibration in different temperature field profiles and consists of 28 lines created by means of the temperature field profile's parallel shift for 50 °C. Every line of the training selection imitates the result of calibration in one temperature field profile along the thermo electrodes. Next 28 lines are occupied by the test selection that completely recreates maximum training selection. Its purpose is to define the correction error of the obtained heterogeneity using the proposed method and decreasing the amount of necessary calibrations.

The aim of this article is to investigate the non-excluded error of the proposed correction method caused by the individual CF drifting speed change in separate sectors of the thermoelectrodes in the exploitation process. Every i sector has its individual deviation of the drifting speed that may be imitated by coefficient K_i, which contains systematic and accidental constituents corresponding to the formula

$$K_i = 1 + k(r_1 - 0{,}5), \quad (3)$$

where r_1 is the accidental numbers in a range from zero to one, $r_1 \in [0;1]$; k is the coefficient, that sets maximum deviations of the individual CF drifting speed of certain thermocouple electrode sectors from value defined according to the results [17].

4. Research Results

First, let's estimate the errors of the proposed method in "ideal" conditions with the absence of speed change in the drift of the thermocouples, i.e. when $k = 0$, then it means that $K_1 = 1$. In the Fig. 2, there are represented five typical dependences of the non-included deviation correction of an irregularity error in 7 – line experimental selection, i.e. while reducing for 4 times the amount of verifications. These dependences are received with the help of a consecutive launch of the neural network training process based on the same experimental and testing selections.

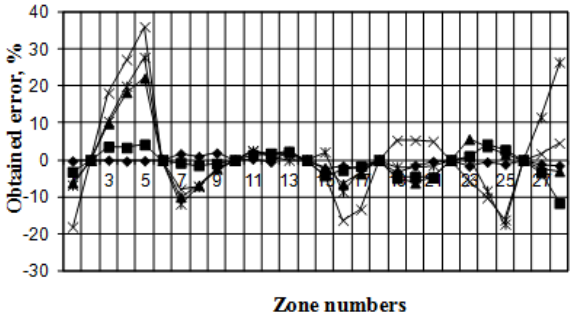

Fig. 2. Non-excluded deviation of the heterogeneity error correction with the drift speed change absence for 7 profiles of the calibration fields (mean error is 4,3 %, maximum – 36 %).

Represented in Fig. 2 diagrams of the non-excluded deviation dependence on the temperature profile change along the thermoelectrodes show the effectiveness of the proposed method in "ideal" conditions. On Fig. 2 and on the following ones on the abscissa axis numbers of the zones are marked according to [23]. Initial profile of the temperature field was formed the following way:

Zones from 1 to 9 – temperature is 0 °C;

Zones from 10 to 17 – temperature gradient is 100 °C per each zone;

Zones from 17 to 28 – temperature is 800 °C.

Change of the temperature field profile while imitating the experimental investigation (verification) of the heterogeneous thermocouple shifts for one zone. Values of the non-excluded deviation from the profile change of the temperature field along the thermoelectrodes are marked along the ordinate axis; the deviations in this experiment were drawn to the maximum value.

As it is presented in the above paragraphs the proposed method allows to reduce the influence upon the result of temperature measuring deviation obtained in the process of thermoelectrodes' heterogeneity exploitation for three times with the change of temperature field profile in wide range (to 800 °C) and for six times with the change of temperature field profile in relatively narrower range (to 400 °C).

To examine the influence upon the error correction from the obtained in the process of thermoelectrode exploitation heterogeneity deviation of the thermocouple's CF sectors electrodes individual drifting speed, i.e. in the variant when $k \neq 0$, which also means that $K_1 \neq 1$, was developed a training selection for which maximum deviations of the individual drifting speed varieties on the CF sectors of the thermocouple's electrodes

were 5 % ($k = 0,1$), 10 % ($k = 0,2$), 15 % ($k = 0,3$) and 20 % ($k = 0,4$). The same as in the previous experiment in this one the errors for the training selection were investigated, they consist of 21, 14 and 7 lines while the amount of test selection always remained 28.

Separate implementations of the non-excluded deviations of the heterogeneity error correction dependence with 7-line training selection (i.e. with the 4 times decrease of the verification amount) and with the maximum individual CF drift speed deviation of the thermocouple's electrode sectors for 5 % are shown in the Fig. 3. As it is represented on the diagrams in the Fig. 3, non-excluded deviations of the error correction from the obtained heterogeneity with maximum deviation of the drift speed for 5 % remains practically not worse from the error with the absence of drift speed changes. Drawing an analogy to the previous experiment the error considerably increases when the temperature field profile changes in wide range (up to 800 °C).

Fig. 4 contains separate implementations of the non-excluded deviation of the heterogeneity error correction dependence with 7 lines of the training selection (i.e. with the 4 times decrease of the verification amount) with the maximum deviation of the individual drifting speed on the CF sections of the electrode thermocouples for 10 %.

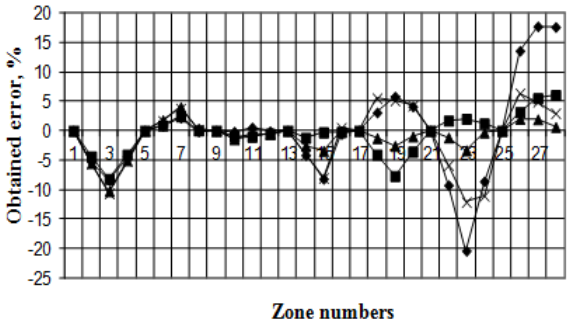

Fig. 3. Non-excluded deviation of the heterogeneity error correction with maximum drifting speed deviation to 5 % for 7 profiles of the calibration fields (average error is 3 %, maximum – 20 %).

As represented on the paragraphs in the Fig. 4 the correction error is not excluded while decreasing the amount of calibration increases to unacceptable values. However, the Fig. 4 shows that such an increase is characteristic only for temperature field profile changes of a wide range (to 800 °C). With the changes of temperature field profile in narrower range (to 400 °C) deviation of the heterogeneity error correction is not higher than 15 %, which means that it allows to decrease for 6 times the influence upon the temperature measurement result from the deviation obtained in the process of thermoelectrode heterogeneity exploitation.

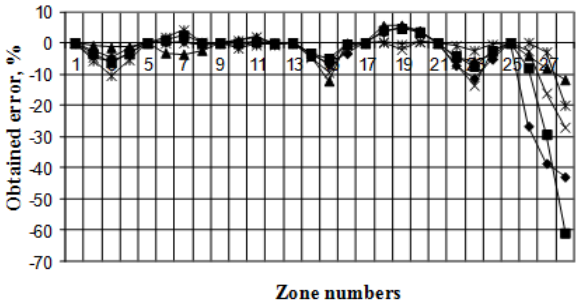

Fig. 4. Non-excluded deviation of the heterogeneity error correction with the maximum deviation of drifting speed to 10 % for 7 profiles of the calibration fields (average verification is 4 %, maximum – 60 %).

In the Fig. 5 separate implementations of the non-excluded deviation of the heterogeneity error correction dependence in 7 lines of training selection (i.e. when the amount of verifications is decreased for 4 times) are shown while the maximum deviation of the individual CF drift speed of the thermocouples electrode sectors is 15 %. As it is shown on the diagrams in the Fig. 5, the mean value of the non-excluded deviation of the error correction, while the amount of calibration is reduced, remains suitable and the maximum error increases to the unaccepted value. However, such increase took place during only one implementation from all four conducted and only in one point. That is why it is unreasonable to consider that the proposed method had exhausted all of its possibilities.

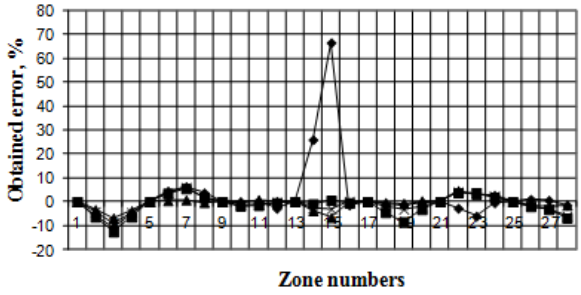

Fig. 5. Non-excluded deviation of the heterogeneity error correction with maximum error of the drifting speed to 15 % for 7 profiles of the calibration fields (average error is 3 %, maximum – 66 %).

In the Fig. 6 separate implementations of the non-excluded deviation of the heterogeneity error correction dependencies are represented with 7 lines of the training selection (i.e. with the 4 times decrease of the measurements amount) and with the 20 % of the maximum error of the CF individual drifting speed of the thermocouple electrodes sectors. As it is seen in the Fig. 6 mean value of the non-excluded deviation of the heterogeneity error correction remains insignificant while maximum error increases to the values that are on the edge of

acceptability. Compared to the previous experiment (see Fig. 5) maximum value of the error is 2 times smaller but the amount of the realizations, during which the error value is abruptly getting bigger, increases. Received value of the maximum correction error provides the decrease of the influence upon the error from the obtained heterogeneity of thermoelectrodes for 3 times.

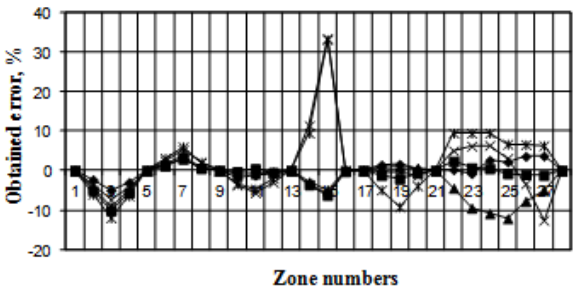

Fig. 6. Non-excluded deviation of the heterogeneity error correction during maximum deviation of the drift's speed to 20 % for 7 profiles of the calibration fields (average error is 4,1 %, maximum – 33 %).

Fig. 7 represents a distribution histogram of the non-excluded deviation of the heterogeneity error correction obtained during calibration of the maximum deviation of the drifting speed to 20 % and with the reduction of the amount of calibration field profiles to 7 (i.e. for the maximum complexity case). As it is shown in the Fig. 7, distribution law of the error correction is close to normal, i.e. the possibility of huge deviations in values estimated by the neural network and the results of the calibration is small. Evaluation of a medium square deviation σ for a separate realization may be defined with the help of the following formula [19]

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i - M)^2} \approx 6\mu V\,, \qquad (4)$$

where $X_i - M$ are the absolute values of the deviation of the error correction from the obtained heterogeneity.

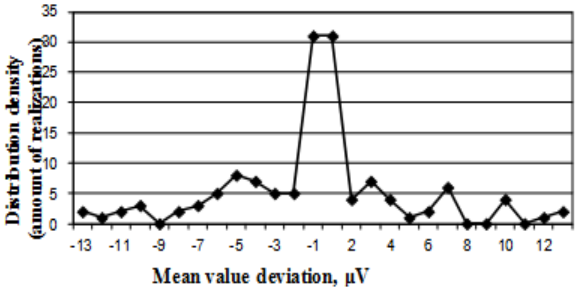

Fig. 7. Distribution histogram of the non-excluded deviation of the heterogeneity error correction with the help of the proposed method.

In this case the approximate estimation of the correction error is defined as $\pm 3\sigma$, and is ±18 μV, i.e. 95 % of the residual error meanings from the obtained heterogeneity after the correction, that doesn't go beyond the limits of ±18 μV or ±0,45°C. Estimation of the residual error from the obtained heterogeneity after the correction for two year probability is *P=0.9* and designates ±10 μV or ±0.25 °C.

On the diagrams in the Fig. 2~6 is represented a non-excluded deviation of the correction error from the obtained one in the process of continuous (1000 hours) exploitation of the heterogeneity for the minimal training selection – corresponding to the data [22] for the three-layer perceptron in further vector amount reduction of the training selection (less than 6 … 8 vectors) training error increases abruptly. That is why it is appropriate to examine the deviation of this error in the process of the amount of vectors reduction in training selection. The diagram of the Fig. 8 shows the mean value dependency of the non-excluded deviation of the heterogeneity error correction from the obtained heterogeneity with the change of training selection from 7 to 28 vectors (with 28 vectors training and testing selections coincide). As it is shown on the Fig. 8, mean value of the error slightly changes and always remains within the acceptable range. In the Fig. 9 the maximum value dependency of the same error is shown while the amount of training selection vectors is changed. In the Fig. 9 there is a representation on how the maximum value of the non-excluded error abruptly increases and the main value extremely for 10 and more times surpasses the mean value of this error.

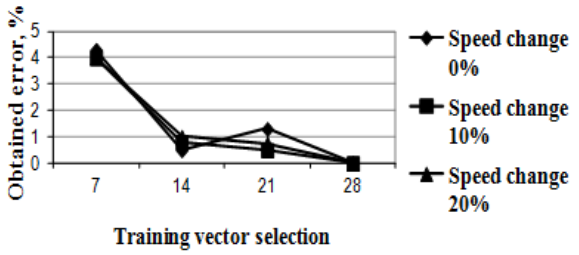

Fig. 8. Increase of the average non-excluded deviation of the heterogeneity error correction during the training selection change.

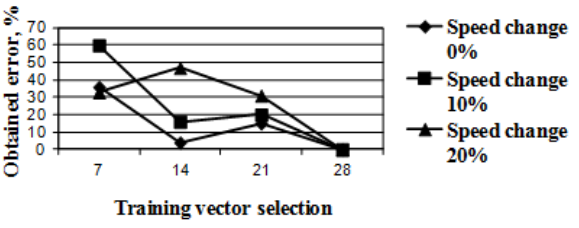

Fig. 9. Increase of the maximum non-excluded deviation of the heterogeneity error correction during the change of the training selection.

5. Conclusions

As it is obvious from the shown above investigations, the proposed in [20, 21] method of the error correction from the obtained in the process of thermoelectric heterogeneity exploitation of thermocouples provides a substantial reduction of this errors' influence upon the result of the temperature measurement even with a considerably huge individual speed change of the CF drift in the separate sectors of their electrodes. The implementation of the neural network in this process to reduce the amount of experimental investigations using the error prognosis from the obtained heterogeneity in different temperature fields allows the reduction of the thermoelectric transformers calibration necessity for several times.

However in the process of the proposed method research it has been noticed that three layered perceptron used in the experiment does not completely satisfy the demands of the proposed method. In a very small error of the prognosis in most cases sometimes occur significant "emissions", i.e. a huge increase of the prognosis error in several times for one point (testing result prognosis for one temperature field profile along the thermoelectrodes). It is characteristic that the error in the neighboring points remains completely acceptable due to the average value of this and other implementations of the method. On this basis we may conclude that the improvement of the prognosis results is possible according to the proposed method using other types of neural networks.

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