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Peculiarities of Application of Contact Methods for Measuring the Temperature of Technological Objects

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Abstract

Contact methods are usually used to measure the temperature of industrial technological objects. When using the contact method to create the necessary conditions for heat exchange, thermal transducer must be in direct contact with the object of study, the temperature of which must be measured. When measuring stationary temperatures, the readings must be taken after a certain time interval from the moment of contact of the thermal transducer with the object of study, when a state of thermal equilibrium is established between them. Measurement of non-stationary temperatures by contact methods is always associated with the occurrence of dynamic errors over time due to the thermal inertia of the thermal transducer. The complexity of the processes of interaction of thermal transducers with heat flows of different nature of the objects of study necessitates the construction of simplified models to obtain practical estimates of the measurement results. Therefore, the article proposes the principles of choosing a thermal transducer to reduce possible methodological errors and estimate the actual errors of measuring the temperature of the objects of study. The conditions that must be met when setting up and conducting experiments to obtain reliable temperature measurement results are given. The article contains reference and methodological materials on measuring the temperature of technological objects by contact methods.

Keywords: temperature; contact measurement methods; thermal transducer; measurement errors; heat flows.

1. Definition of the scientific problem chosen for research

A contact thermal transducer is any transducer based on a certain principle of converting temperature into another physical quantity that can be measured directly. In this case, its thermal interaction with the object of study (solid, liquid, gas flow, etc.) is based on direct thermal contact. The quality of this thermal contact is a determining factor that characterizes the error of temperature measurement by this thermal transducer.

To assess the measurement error of a contact thermal transducer, it is necessary to consider all thermal processes in which the thermal transducer participates, from the point of view of the theory of heat transfer. It is advisable to consider heat flows of various nature supplied to the thermal transducer from the object of study and flows removed from it into the environment.

The complexity of the processes of interaction of the thermal transducer with heat flows necessitates the construction of simplified models to obtain practical estimates of the measurement error. But with all simplifications, it is necessary to consider the conditions of use of thermal transducers and the thermophysical properties of their structural materials, which is not always possible. Therefore, based on the above, it is advisable to offer an approximate scheme for the correct selection of a thermal transducer to reduce the measurement error to a practically possible value.

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2. Analysis of recent publications and research works on the problem

The authors' analysis of publications and research on contact methods of temperature measurement of various technological objects shows that the most widely used in modern temperature measurement systems are thermal transducers based on electrical temperature conversion, i.e. resistance thermal transducers and thermoelectric transducers (thermocouples) [1]-[5].

Currently, there are no general theoretical foundations for the development and application of contact methods of temperature measurement, although some issues of designing contact thermal transducers for some specific conditions of application and the possibility of reducing the measurement error have been worked out [6]. Therefore, in this article we offer the necessary reference and methodological materials on the correct choice of contact methods of temperature measurement to achieve the minimum possible value of the temperature measurement error.

3. Formulation of the purpose of the article

The article aims to familiarize scientists, research engineers and designers involved in temperature measurements with the theoretical foundations and practical implementation of contact thermal transducers while ensuring the minimum value of the measurement error in various application conditions.

The article identifies the following main research objectives: the correct choice of the measurement method and ways to reduce methodological errors in temperature measurement.

4. Presentation and discussion of the research results

4.1. Thermal processes during contact temperature measurement

The quality of thermal contact between the thermal transducer and the object of study determines the time of establishing its readings and in most cases is a determining factor characterizing the error of temperature measurement by this thermal transducer. Therefore, an important property of a contact thermal transducer is its suitability for ensuring sufficient heat exchange under the conditions of installation on the object of study so that the temperature difference between it and the object under study is minimal. This difference determines the methodological error of the thermal transducer for these measurement conditions. Given that a contact thermal transducer is any transducer based on an arbitrary principle of converting temperature into a directly measured physical quantity, the thermal interaction of which with the object under study (solid, liquid, gas, etc.) is based on direct thermal contact.

To assess the methodological error of a contact thermal transducer, it is necessary to consider all thermal processes in which the thermal transducer participates, from the point of view of the theory of heat transfer [7,8]. To do this, it is first necessary to determine the heat flux dissipated (at elevated temperatures) into the environment by the protruding parts of the thermal transducer. This heat flux is continuously removed from the thermal transducer and, when thermal equilibrium is established, the same heat flux is continuously supplied to it from the object of study, the temperature of which is measured through the thermal resistance placed between them. That is, a contact thermal transducer in principle always has a lower temperature than the object of study that is in thermal contact with it.

If the heat transfer coefficient of the thermal transducer during operation at the object has a constant value, then this temperature difference can be considered in the calibration process. When the heat transfer coefficient changes under operating conditions, such a type of methodological error occurs.

It is also necessary to consider that heat transfer occurs through radiation from the surface of a heated solid object of study. Therefore, the temperature of its surface is often significantly lower than the temperature inside of it. This difference will be determined by the ratio of heat flows. If the heat flow dissipated by the thermal transducer is greater than the heat flow lost by the surface of the object of study because of heat transfer through radiation, then the temperature of this surface area measured by the thermal transducer will be lower than the temperature of neighboring areas. If the reverse ratio of heat flows occurs, then the temperature of the surface area under the thermal transducer will be higher than that of neighboring areas.

A continuous and constant flow of heat from the object of study to the thermal transducer is possible only when the object has a practically unlimited supply of heat. In many cases of industrial temperature measurements, this condition is met. However, in practice, there are often cases when the thermal transducer and the object of study have comparable masses. Then the thermal contact of the thermal transducer and the object under study with significant differences in their initial temperatures will lead to a significant change in the temperature of the latter. This type of error can be reduced by pre-equalizing their temperatures before their thermal contact.

Therefore, for these conditions, the criterion for the suitability of a thermal transducer for measuring temperature in the given conditions should be the change in the temperature of the object under study, which occurs because of its heating (or cooling) of the thermal transducer from the initial to the final temperature. For such cases, it is advisable to take one third of the value of the instrumental error of the measuring system as the permissible change in the temperature of the object under study [1]. This determines the limit of application of contact methods for measuring the temperatures of small objects under study.

Another circumstance that may limit the application of contact methods is the possible disruption of the course of physicochemical processes in the object under study, caused by the installation of a thermal transducer in it.

Measurement of non-stationary temperatures by contact methods is always associated with the emergence of constantly present and time-varying dynamic errors, which are due to the thermal inertia of the thermal transducer [9]. This type of error can be considered and excluded by introducing appropriate calculation corrections.

The above analysis shows the complexity of the processes of interaction of thermal transducers with heat flows of various nature under complex initial and boundary conditions. Therefore, to obtain practical estimates of the temperature measurement error, simplified mathematical models of processes are usually built. But with such simplifications, it is imperative to consider the conditions of use of thermal transducers and the main thermophysical characteristics of materials, which is not always achievable using simple means.

In this regard, an approximate scheme for selecting a thermal transducer is proposed to reduce methodological errors to a practically possible or necessary value and to estimate real or permissible errors.

1) Based on the analysis of measurement tasks, operating conditions, requirements for technical means of the measuring path, make a choice of possible temperature meters according to the principle of operation. At the same time, determine the measurement locations and ensure conditions for maximum reduction of systematic errors.

2) Substantiate the values of permissible measurement errors based on tasks, the solution of which requires information about temperature values with a given reliability.

3) Pre-evaluate the heat exchange conditions that will determine the operation of the temperature transducer. Based on the worst possible conditions (minimum heat exchange intensity, maximum possible temperature change rate, maximum temperature difference between the object under study and the environment surrounding the thermal transducer, etc.), evaluate the possible maximum errors for each of the thermal transducers proposed for use. In this case, it is advisable to choose the temperature change rate for that section of the temperature curve that is of greatest interest. This may be a transitional mode or a mode of smooth monotonic temperature change. Preference should be given to that thermal transducer that has a certain margin of accuracy or some operational advantages over others.

4) If the heat transfer conditions and the requirements for the values of permissible errors are such that none of the proposed thermal transducers meet them, then it is advisable to choose the most suitable thermal transducer for the given measurement conditions and to introduce appropriate corrections into the results obtained with its help. Note that to be able to introduce corrections, it is necessary to perform additional measurements to obtain the necessary information about the thermal operating conditions of the thermal transducer. The volume of this information may vary, but data on heat transfer coefficients and on the temperature difference between the object under study and the environment surrounding the thermal transducer at the place of its installation is necessary. If the operating mode of the object under study is relatively stable from experiment to experiment, then after a single receipt of information, there is no need for repeated measurements. Under variable conditions, these measurements must be repeated.

5) Carry out measurements and, depending on the type of the obtained temperature curve in time, evaluate the corrections calculated for the values of the parameters of the thermal transducer that correspond to the thermal conditions of measurement. The need to introduce corrections depends on their numerical value, the overall accuracy of the measuring path and the value of the permissible measurement error based on the general rules of the theory of errors.

In general, it is necessary to strive for the measuring instruments to have the necessary margin of accuracy for the given measurement conditions and the need to introduce corrections to exist only in exceptional cases. But in cases where the margin of accuracy is absent, it is necessary to use either corrections or limit estimates of methodological errors.

4.2. Distribution of permissible errors

When measuring the temperature of the object under study, it is first necessary to distinguish from the total permissible error, which is normalized by the requirements for the accuracy of the study of this process, those of its components that can be defined as:

- permissible instrumental error of the entire measuring path Δ_i;
- permissible methodological measurement error Δ_m;
- permissible dynamic measurement error Δ_d.

If we consider a stationary temperature process and the duration of the measurement operation is not significantly limited, then the dynamic error will be absent and the total permissible error will be distributed between the instrumental and methodological errors.

All three components Δ_i, Δ_m and Δ_d can contain both systematic and random parts. Systematic parts that are subject to evaluation are subject to exclusion by introducing appropriate corrections and they cannot be considered as components of the permissible error. The uncertainty of these corrections, estimated by calculation or experiment, does not exclude systematic errors, and they are attributed to random errors.

When isolating the components of the total permissible error, it is advisable to consider the following considerations. If the total permissible error is normalized correctly, then it should be considered as a characteristic of the expected random errors of measurements and a certain probability should be attributed to it, for example, 95%, which corresponds to the confidence interval 2σ. Then all components Δ_i, Δ_m and Δ_d should have the same confidence probability. Since all these three components are mutually independent, then the following relation is valid [10], [11]:

$$\Delta = \sqrt{\Delta_i^2 + \Delta_m^2 + \Delta_d^2}\ . \qquad (1)$$

In temperature measurements, methodological errors are the most difficult to reduce. Therefore, it is advisable to first try to reduce the instrumental Δ_i and dynamic Δ_d components of the measurement error as much as possible by appropriate selection of measuring instruments, and then, using their values, determine the value of the methodological component Δ_m using formula (1).

It should be considered that increasing the accuracy class of the measuring equipment used leads to an increase in its cost and quite often to a decrease in its reliability. Therefore, the desire to reduce the instrumental component Δ_i of the error is not always justified and the task of reducing the measurement error requires finding an optimal solution.

4.4. Selection of the measurement method and measuring equipment

To obtain reliable results from measuring the temperature of technological objects, the design and conduct of experimental studies must ensure the fulfillment of the following conditions:

- correct choice of measurement method and measuring instruments;
- correct consideration of methodological errors that arise in the given conditions of temperature measurement.

It should be noted that the task of selecting the measurement method and measuring instruments is quite complex, since it is necessary to look for the optimal solution considering many often contradictory factors. Quite often, there are cases when the task cannot be successfully solved and the desired temperature values are found indirectly using the results of measurements of other physical parameters of the object under study, related to temperature by certain dependencies.

Below are the main factors that determine the choice of the measurement method and measuring instruments.

4.4.1. Range of measured temperatures

This factor is quite important. Thus, if for measuring low and high temperatures it is possible to choose contact methods, then with an increase in the temperature range, the number of methods becomes more and more limited. This limitation arises in relation to primary transducers because high temperatures significantly affect the systematic change in their calibration characteristics. Therefore, the question of the possibility of using this transducer should be resolved considering the duration of its operation and the rate of change in the calibration characteristic when measuring high temperatures. The upper temperature range of applications is the value of the measured temperature at which, during the required time of operation of the transducer, the change in its calibration characteristic will not exceed the permissible value. Using the transducer when measuring temperatures that are too high for it leads to its destruction.

4.4.2. Chemical interactions

A significant influence on the stability of the thermotransducer at high temperatures is its chemical interaction with the environment whose temperature it measures, as well as the interaction of various materials that make up its composition. Chemical interaction is especially pronounced at high temperatures, when some of the constituent materials of the thermotransducer become quite active.

This group of influences also includes the catalytic effect that occurs on the surface of platinum group metals when measuring temperature in combustible gas mixtures. Therefore, the readings of thermotransducers that have parts that are in direct contact with such mixtures do not characterize the temperature established between the thermotransducer and the medium under study, but a higher one due to catalytic heating.

The chemical interaction of the environment under study and the thermotransducer is often the main reason for the instability of its calibration characteristic when measuring high temperatures. Therefore, to ensure reliable operation in aggressive, and sometimes oxidizing environments, it is necessary that the protective housing of the thermal transducer, which separates the sensitive element from the medium under study, be practically gas-proof.

4.4.3. Dynamics of the studied process

When choosing a thermal transducer for the study of non-stationary temperature processes, special attention should be paid to its dynamic characteristics and the characteristics of the elements of the measuring path. First, it is necessary to determine whether the process is stationary or non-stationary. Such a determination can be made only by focusing on a certain measurement time interval. A stationary process should be considered one in which, over a sufficiently large time interval, the temperature change does not exceed the limits of random measurement errors.

From the point of view of the coordination of the dynamic characteristics of the thermal transducer and the entire measuring path with the time characteristics of the measurement process, the degree of stationarity should be determined in relation to the duration of a separate measurement, that is, the time required to obtain a separate reference. Therefore, a stationary process should be considered one in which, over the time required to perform one measurement of the temperature change, the random error of the measuring path does not exceed the total. Since the assessment of such a random error is probabilistic, the degree of process stationarity is also a probabilistic characteristic, and for the correct qualification of the process, a certain confidence probability should be considered. Therefore, for measuring stationary temperatures, the thermal transducer and the entire measuring path should be selected with such dynamic characteristics that the time for establishing readings for a single reference meets the requirements of the experiment.

When selecting a thermal transducer and elements of the measuring path for measuring a non-stationary temperature process, it is necessary that the dynamic error due to the thermal inertia of the thermal transducer does not exceed that part of the permissible total error that can be interpreted as the permissible dynamic error.

4.4.4. Accuracy class of measuring system links

When determining the required accuracy class of measuring and recording measuring instruments, it should be borne in mind that the accuracy class is determined by the value of the permissible basic and additional errors, expressed as a percentage in relation to the entire measurement range [10]. The corresponding relative error, attributed to the measured temperature itself, will be the greater the closer its value is to the beginning of the scale. For example, in a measuring device of accuracy class 0.5 with a scale from 100 to 500 °C, the absolute value of the permissible error is 2 °C at any point on the scale. Its relative value for this case can vary from 2/500 (0.4%) at the end of the scale to 2/100 (2.0%) at the beginning of the scale. Therefore, it is advisable to choose measuring instruments with such measurement ranges that the expected value of the measured temperature falls into the last third of the scale for stationary and smoothly varying temperatures. For measuring fluctuating temperatures - in 2/3, and in the presence of strong temperature pulsations - in 1/2 of the scale.

If the calculation of relative errors is performed in relation to temperature, then it is advisable to conduct it not to the absolute value of the temperature, but only to the temperature interval that covers the process under study.

Since depending on the scale (Kelvin or Celsius) in which the given temperature is expressed, the relative measurement error will have a different value, which cannot be considered acceptable.

4.4.5. Sensitivity of the measuring device

Depending on the required measurement accuracy, it is necessary to ensure the appropriate sensitivity of the measuring path, which characterizes the change in the output value of the thermal transducer when the measured temperature changes by one degree.

It is incorrect to state that the most sensitive measuring device can provide the highest measurement accuracy, which is sometimes not even necessary for this study. The use of a measuring device with excessively high sensitivity can create a false idea of the dynamics of the process under study. Such a device may be difficult to maintain in these operating conditions, its readings may be affected by adverse factors, which can lead to an increased and not typical spread of readings for this measurement.

The use of a measuring device with low sensitivity will not allow for recording small, but characteristic temperature fluctuations for this process. As a result, a false idea of high temperature stability in this technological process may arise.

Measurement of small quantities (for example, small temperature differences) can be complicated at values close to the sensitivity threshold, which is taken as the minimum value of the change in the measured quantity, which causes a noticeable change in the instrument readings. Note that when measuring deterministic signals, the sensitivity threshold of the measuring instrument should be 2-3 times smaller than the minimum value of the measured quantity. In measuring systems with information transmission in code form, the signal-quantization step is taken as the sensitivity threshold of the system by level [10], [11].

5. Conclusion

The article provides reference and methodological information on measuring the temperature of technological objects by contact methods. Thermal processes during contact temperature measurement are considered, which are the determining factors of the measurement error.

An approximate algorithm for selecting a thermal transducer to reduce methodological errors in temperature measurement is proposed. The main factors that determine the choice of temperature measurement method and measuring instruments are presented, depending on the measurement range, chemical interaction with the studied environment, dynamics of the studied process, accuracy class and sensitivity of measuring instruments.

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Особливості застосування контактних методів для вимірювання температури технологічних об’єктів

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Анотація

Для вимірювання температури промислових технологічних об’єктів зазвичай застосовують контактні методи. При застосуванні контактного методу для створення необхідних умов теплообміну термоперетворювач повинен знаходитися в безпосередньому контакті з об’єктом дослідження, температуру якого необхідно виміряти. При вимірюванні стаціонарних температур відлік показів необхідно здійснювати через деякий інтервал часу з моменту контакту термоперетворювача з об’єктом дослідження, коли між ними встановиться стан теплової рівноваги. Вимірювання нестаціонарних температур контактними методами завжди пов’язано з виникненням в часі динамічних похибок, обумовлених термічною інерцією термоперетворювача. Складність процесів взаємодії термоперетворювачів з тепловими потоками різної природи об’єктів дослідження обумовлює побудову спрощених моделей для отримання практичних оцінок результатів вимірювання. Тому в статті запропоновано принципи вибору термоперетворювача для зменшення можливих методичних похибок і оцінки дійсних похибок вимірювання температури об’єктів дослідження. Наведено умови, які необхідно виконати при постановці і проведенні експериментів для отримання достовірних результатів вимірювання температури. Стаття містить довідковий і методичний матеріали з вимірювання температури технологічних об’єктів контактними методами.

Ключові слова: температура; контактні методи вимірювання; термоперетворювач; похибки вимірювання; теплові потоки.