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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

DEVELOPMENT OF METROLOGICAL ASSURANCE OF THERMODYNAMIC TEMPERATURE MEASUREMENTS WITH INNOVATIVE METHODS

Speciality: 3336.01 – Metrology and metrological assurance

Field of science: Technical sciences

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BAKU – 2025

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The One-time Dissertation Council, registered under number BFD 2.02/1 with the Supreme Attestation Commission under the President of the Republic of Azerbaijan, acting on the basis of the ED 2.02 Dissertation Council functioning under the Azerbaijan State Oil and Industry University (ASOIU) PLE under the Supreme Attestation Commission under the President of the Republic of Azerbaijan

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GENERAL CHARACTERISTICS OF THE WORK

Relevance and degree of development of the topic. Improving the quality indicators of heavy and light industry, including agricultural products, which constitute the main and integral part of the economy of the Republic of Azerbaijan, is currently of particular importance. The most important way to improve the quality indicators of products produced in the mentioned industrial sectors is to increase the accuracy of measuring instruments used in those sectors, minimize their errors and develop metrological support. Solving the mentioned metrological problems in industrial and manufacturing sectors creates the basis for achieving great economic indicators.

The relevance of the topic is reflected in the Law of the Republic of Azerbaijan "On Ensuring the Unity of Measurements", which defines the legal and organizational basis for ensuring the uniformity of measurements in the Republic of Azerbaijan, in accordance with Article 94, Part I, Clause 24 of the Constitution of the Republic of Azerbaijan. With this Law, a new stage of development of measurement tools, measurement methods, measurement principles, metrological assurance and other such important issues has started in the country. This Law is characterized by the transition of metrological activity from the principle of administrative management to the principle of legislation. Also, the Law, while retaining the principle of the state nature of the works performed in the field of measurement and metrological assurance, creates conditions for the harmonization of the existing measurement system with international practice.

Currently, due to the intensive development of science and technology, the importance and volume of measurement information is constantly increasing. Solving modern scientific and technical problems requires high measurement accuracy that can be reconciled with standard measurements. In some cases, it is necessary to measure temperature, pressure, mass, consumption measurements with an error not exceeding 10^{-3} %, and linear displacements not exceeding 10^{-4} %. The specified measurement accuracy must be ensured during significant changes in temperature, humidity and pressure under production conditions.

Progress in technology, industry and agriculture in all fields, as well as in natural sciences, is determined by complete and accurate information about physical, chemical, biological and other phenomena and processes, about the properties of matter and materials, which can only be found through measurements. High metrological characteristics of measuring methods and tools enable progress in scientific research. Solving scientific problems, in turn, opens up new ways of improving measurements.

The state of modern measurement technique, measurement theory and results processing methods allow to achieve a very high accuracy of the measurement result. It is known that no production process can be imagined without temperature measurements. Errors during temperature measurements lead to a decrease in product quality during the production process, an increase in waste products, loss of material resources, as well as accidents in production. In this regard, as mentioned above, accurate and correct temperature measurement plays an indispensable role in the production sector. Therefore, research on increasing the accuracy of temperature measurement results and developing metrological support is of particular importance.

A number of local and foreign researchers have dealt with the problems of metrological assurance of thermodynamic temperature measurements, but in order to ensure the minimization of errors that may occur in the conducted studies, the issues of modeling the improvement of metrological assurance by taking into account the environmental conditions and external factors affecting the measurement result during thermodynamic temperature measurements have not been considered.

Thus, the development of mathematical models for improving the metrological support of thermodynamic temperature measurements is a pressing scientific and technical issue and is of great importance in terms of improving quality in production processes, reducing waste products, economic efficiency, and minimizing life risks.

The object and subject of the research. The object of the research is thermodynamic temperature measurements, which include the accurate and reliable determination of temperature, which is considered the main physical parameter in the processes of measuring and transferring thermal energy, the measurement methods and tools used for this purpose, as well as the metrology problems encountered in this field. The subject of the research is the consideration of environmental conditions and external factors that affect the measurement result during thermodynamic temperature measurements.

The purpose and objective of the research. The purpose of the research conducted is to develop improved metrological support by taking into account environmental conditions and external factors that affect the measurement result during thermodynamic temperature measurements..

The main objectives of the research are as follows:

1. Relations between thermodynamic temperature measurements and metrological assurance issues were determined.
2. Selection of the main parameters of metrological assurance of thermodynamic temperature measurements is justified.
3. Mathematical, functional and structural schemes of the system for improving the metrological assurance of thermodynamic temperature measurements with an innovative method were developed.
4. Mathematical models of the metrological assurance system of temperature measurements were developed based on the theory of thermodynamics.
5. Obtaining objective data from monitoring and measurements to accurately assess model parameter errors and ensure parameter reliability.
6. Local and international experimental studies and tests were conducted for the approval of the theoretical approaches proposed for the assessment of the accuracy of thermodynamic temperature measurements and improvement of metrological assurance.

Research methods. Innovative methods of increasing the accuracy of thermodynamic temperature measurements, minimizing errors and improving metrological assurance, elements of thermodynamics and set theory, probabilistic and mathematical statistics, graphical and mathematical modeling methods were used in the dissertation work.

The main provisions put forward for defense. Empirical works aimed at increasing the efficiency and accuracy of observation, measurements and monitoring were taken as the main direction of improving the metrological support of thermodynamic temperature measurements using innovative methods.

The main scientific propositions of the dissertation presented for defense are:

1. Generalized functional and structural schemes of the metrological support system of thermodynamic temperature measurements.
2. Mathematical models of the metrological support system developed on the basis of objective data of monitoring and measurements of the parameters of thermodynamic temperature measurements.
3. Method for assessing the uncertainty of the measurement results of the controlled parameters of thermodynamic temperature measurements.
4. Innovative method for increasing the accuracy of thermodynamic temperature measurements.
5. Results of experimental studies of the methods and models proposed in the dissertation in the metrological support system at a real production enterprise.

Scientific novelty of the research. The scientific novelty of research results consists of the following:

1. Improved functional and structural schemes of the metrological assurance system of thermodynamic temperature measurements with innovative methods were developed;
2. The objective values of the controlled parameters of thermodynamic temperature measurements were determined;

3. Mathematical and graphic models of the metrological assurance system based on honest results of technical measurements were developed;

4. An innovative method of increasing the accuracy of thermodynamic temperature measurements was developed;

5. Analytical expressions were obtained to evaluate the parameters of the models, including the output parameters of the thermodynamic temperature measurement results, which are true for all distribution laws.

The integrity of the obtained results is ensured by the correct use of appropriate mathematical apparatus and formulas, the accuracy of temperature measurements based on objective data on quality parameters, as well as their computer processing.

Theoretical and practical value of the research. The theoretical and practical importance of the research consists of the following:

1. The developed mathematical modeling method, which expresses the reliability parameters of the metrological assurance of thermodynamic temperature measurements, allows for increasing the accuracy of temperature measurements without creating additional structures.

2. The proposed modeling methods can be used to improve and modernize the metrological support of thermodynamic temperature measurements and will allow for the improvement of metrological support by obtaining measurement results with stable indicators and a high level of accuracy during temperature measurements.

3. The recommended method of estimating measurement errors when improving the metrological support of thermodynamic temperature measurements will allow obtaining stable values when normalizing the accuracy indicators of measurements.

Approbation and application of the research: The main provisions and results of the research were presented and discussed at the scientific-methodological seminars of the Department of "Instrument Engineering" of ASOIU, as well as at the annual scientific-technical and scientific-methodological conferences of the professorial staff of ASOIU.

Important scientific and experimental results were presented in the form of reports and theses at national and international scientific and technical conferences.

– Republican Scientific and Technical Conference of students and young researchers on the topic "Youth and Scientific Innovations" dedicated to the 96th anniversary of the birth of the National Leader Heydar Aliyev, AzTU, Baku, Azerbaijan, May 02-04, 2019.

– The first international scientific and practical conference on “Modern information, measurement and control systems: Problems and prospects” (MIMCS’2019) dedicated to the 100th anniversary of ASOIU. ASOIU, Baku, Azerbaijan, July 01-02, 2019.

– Online scientific conference of young researchers and doctoral students dedicated to the 100th anniversary of the Azerbaijan State Oil and Industry University, ASOIU, Baku, Azerbaijan, 07-08 May 2020.

– Second international scientific and practical conference on the topic “Modern information, measurement and control systems: Problems and prospects” (MIMCS’2020”) dedicated to the 100th anniversary of the ASOIU, ASOIU, Baku, Azerbaijan, 07-08 December 2020.

– Europäische Akademie der Naturwissenschaften (in Hannover) e.V. the International Symposium EANW, Hannover, Germany, 2020.

– Republican scientific and technical conference of students and young researchers dedicated to the 98th anniversary of the birth of the National Leader Heydar Aliyev on the topic “Youth and scientific innovations”, AzTU, Baku, Azerbaijan, 06-07 May 2021.

– Young researchers dedicated to the 98th anniversary of the birth of the National Leader Heydar Aliyev online scientific conference of researchers and doctoral students, ASOIU, Baku, Azerbaijan, May 21, 2021.

– International Scientific and Practical Conference // Sustainable Development of Economy and Management: Problems and Perspectives, BMU, Baku, Azerbaijan, December 24-25, 2021.

– 1st International Scientific and Practical Internet Conference, WayScience, Dnipro, Ukraine, May 05-06, 2022.

– “Modern Information, Measurement and Control Systems: Problems, Applications and Perspectives’2022” (MIMCS’2022). Third International Scientific – Practical Conference, Antalya, Turkey, November 04-05, 2022.

– “Khoshbakht Yusifzadeh Readings” International Scientific and Practical Conference on “Oil and Gas Resources and Geoecological Problems of the Caspian Region”, Baku, Azerbaijan, December 04-05, 2024.

The name of the institution where the dissertation work was performed. The dissertation work was performed at the “Instrument Engineering” Department of the “Azerbaijan State Oil and Industry University” PHS, tests were carried out in the Metrological Assurance and Calibration Laboratory of the “Oil and Gas Scientific Research and Project” Institute of SOCAR, as well as in the technological processes and Calibration Laboratory of the Standardization and Metrology Department of the company.of “MKT Production and Commercial” LLC.

The developed innovative methods and models were recommended for application in improving the metrological assurance of thermodynamic temperature measurements. An act on the application of the developed proposals and recommendations was attached to the dissertation work.

The total volume of the dissertation, indicating the volume of structural sections. The dissertation consists of an introduction, 3 chapters, conclusions, a bibliography listing 109 sources, and 176 pages including 36 figures and 11 tables. The dissertation, excluding the table of contents, tables, figures, and the list of used literature, has a total length of 207,121 characters (introduction 13,248, chapter I 64,745, chapter II 68,371, chapter III 56,966, and conclusions 3,791).

THE CONTENT OF THE DISSERTATION

In the introduction, the relevance of the topic of the dissertation is justified, the goals and issues of the conducted research are explained. The results containing scientific innovations are noted and their practical importance is indicated.

In the first chapter, the state of temperature measurement processes in industrial enterprises and production processes, existing methods are analyzed and the main issues to be fulfilled in the dissertation work are defined.

It has become clear that the issues of metrology and measurement technology are becoming more and more relevant in our time, because they determine the progress in the development of production processes. Metrological assurance and its control are the main means for the certification of quality systems and the production of quality products. The technological stability of production depends decisively on their condition. Therefore, the need to pay special attention to metrological assurance issues in the main parameters of technological processes, especially during temperature measurements, has been highlighted.

It has been shown that at present scientific and technical progress is inextricably linked with the continuous improvement of measurement technology. This is directly related to increasing accuracy in both thermometry and other traditional fields. According to some expert estimates, thermodynamic temperature measurements account for about 30 % of all measurements carried out in the national economy, and thousands of scientific and technical publications are compiled on this topic every year.

Thermometry is presented as a section of technical physics that studies the methods and means of measuring temperature, the theoretical foundations of methods for constructing thermodynamic and practical temperature scales and standards, and exemplary temperature measuring instruments created on this basis. Temperature determines the thermal state of the body and the direction of heat transfer. Temperature dependences of physical properties of substances can be used as a basic tool for temperature measurement and temperature scale construction methods. The temperature scale is evaluated as a series of consecutive temperature values formed according to the selected sign, which determines the relationship between the thermometric parameter and temperature.

It is difficult to give an example of a production process, technological field or industrial enterprise where it is not necessary to measure the temperature of solid, liquid or gaseous bodies. In fact, the intensity and direction of solid, liquid and gaseous changes are determined by the most important physical quantity - heat flow[1]. At the same time, it was noted that the choice of methods and means for measuring thermodynamic temperature in each specific area is determined by its characteristics. For this reason, the improvement of metrological support for thermodynamic temperature measurements has been studied as a special and important issue.

The establishment of a metrological assurance system for thermodynamic temperature measurements and its role in the production process is determined by the fact that the measurement relationship of the systems is the main source of information about the state of the environment and technological parameters during its development, production, testing, control stages and operation. It is known that the reliability of thermodynamic temperature information, the accuracy and uniformity of the measurements performed have a direct impact on the level of technical characteristics of the manufactured products, their quality and competitiveness. Therefore, one of the most important tasks for the production of high-quality and competitive products is the improvement of the normative, methodological and technical base that ensures the uniformity and accuracy of measurements, especially temperature measurements, as well as the reconstruction of the metrological assurance system in accordance with modern requirements.

This chapter also notes that currently, work on temperature measurements and their metrological support constitutes a significant part of the total labor costs for the development, testing and

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[1] Thomas D. McGee. Principles and Methods of Temperature Measurement, John Wiley & Sons, 2014, pages 581.

production of products. Despite the difficult economic situation, a significant part of the obligations imposed on the metrological support of thermodynamic temperature measurements has been fulfilled, mainly due to the strong metrological base created over the past decades. However, despite this, as a result of the continuation of negative trends in the obligations imposed on the metrological support of temperature measurements, it is becoming increasingly difficult to maintain and further expand the existing metrological base. Such negative trends include a tendency to violate the fundamental principle of balanced funding levels and advanced technical characteristics of the development of systems, tools and methods of metrological support.

Currently, there is a definite and unequivocal trend regarding the impossibility of competitive product production, not only abroad, but even in the domestic market, without meeting the metrological requirements of thermodynamic temperature measurements. Previously, there were no serious negative consequences due to unreliable measurement results during temperature measurements, but today it has been determined that such requirements for measurement quality are sufficiently present [1].

From the above, it was concluded that the highest and ultimate goal of the metrological assurance of thermodynamic temperature measurements is to ensure the required specifications, efficiency and safety of use, increase measurement accuracy, reduce the amount of waste products, minimize unnecessary costs, and thus improve the quality of the manufactured product. Taking all this into account, it has been shown that the issue of improving the metrological support of thermodynamic temperature measurements is extremely urgent in the current difficult economic conditions.

As a result of the analysis, the issues raised by the research were investigated. As a result, the issues of conducting future research were set, including the development of improved functional and structural schemes of the metrological support system of thermodynamic temperature measurements using innovative methods in order to identify the main elements that affect the results during the technological measurements performed, the determination of objective values of the controlled parameters, and the development of an innovative method for increasing the accuracy of temperature measurements.

In the second chapter, the theory of thermodynamic temperature measurement was studied, the shortcomings of the traditional temperature measurement methods were investigated, and the metrological features of the measuring instruments that could be used with the innovative method were studied.

It has been found that the most common method for measuring temperature is to increase the accuracy of the sensors by mounting them directly in a thermowell. A thermowell is a component of a temperature measurement device that acts as a protective barrier between the temperature sensor and the process[2]. A thermowell is required to place a thermosensor in the process, as without it the sensor cannot withstand high pressure and corrosive or erosive fluids [10].

A thermowell sensor can be placed in the process to measure temperature directly (Figure 1), but this can lead to leakage and safety risks [19][3].

Due to the fact that the thermowell is in direct contact with the process, it has been determined that it is important to take into account a number of nuances during its design and installation[4]. The temperature of the process fluid affects the design, installation, and safe operation of the thermowell. Process calculations performed in accordance with ASME PTC 19.3TW are performed to ensure proper thermowell installation, but such calculations are based on specific process data. If the process parameters are different from those used to calculate the vortex flow frequency, the thermowell may no longer be suitable for the process [24].

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[2] T.W.Kerlin, M.Johnson. Practical thermocouple thermometry, 2nd edn. International Society of Automation, Research Triangle Park, 2012.

[3] E.Webster. Drift in Type K bare-wire thermocouples from different manufacturers. Int. J.Thermophys 2017, Volume 38, pp.70-72

[4] E.Webster. Thermal preconditioning of MIMS Type K thermocouples to reduce drift. Int. J. Thermophys 2016, Volume 38, pp.25-27.

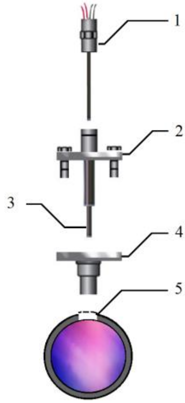
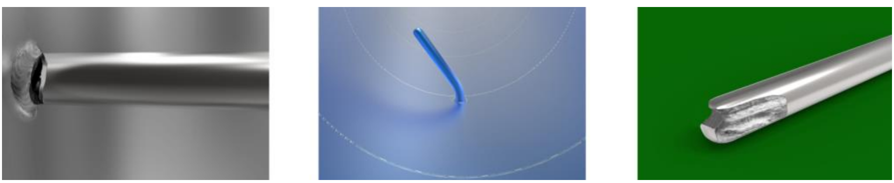


Figure 1. Components of a thermocouple using a thermowell:

1 - primary converter; 2 - thermowell flange; 3 – thermowell;
4 - technological flange, plug and welding connection;
5 - hole in the pipe.

It has been found that failure to monitor the specified parameters can lead to material wear, damage and eventual failure of the thermowell (Figure 2). To reduce this risk, eddy current frequency calculations are often performed several times for each measurement point and for different process options at different temperatures, pressures, and flow rates.



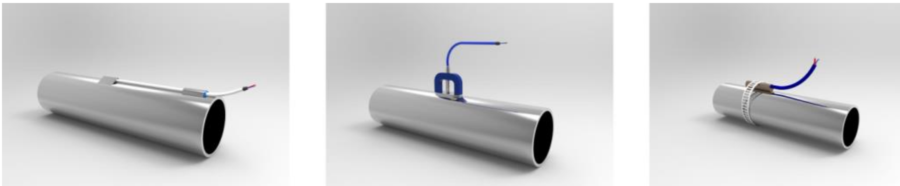
1 2 3

Figure 2. Examples of thermowell failure:

1 - breakage; 2 - deflection; 3 - abrasion.

It has been shown that all of this increases the complexity of the thermowell design, which may need to be modified when process conditions change during thermodynamic temperature measurements. Thermowell design requirements include sheath profile, immersion depth, material type, process connection type, wire length, tip thickness, hole diameter, and other parameters. These parameters can lead to the occurrence of errors during temperature measurements and the systematization of these errors in a certain time interval. In addition, it was determined that additional difficulties may arise for the use of thermowells when conducting thermodynamic temperature measurements in small-diameter pipes using the traditional method. Due to the influence of the thermowell's ambient temperature and other external temperature sources on the thermal conductivity, the temperature measurement error, that is, the conductivity error, if the immersion depth does not exceed 10 times the diameter of the thermowell tip, this ratio will significantly affect the accuracy. In small diameter pipes, this requirement is often not met due to the ratio of the thermocouple length to its end diameter. For example, a thermocouple with a tip diameter of 1 cm requires a minimum insertion depth of 10 cm to avoid thermowell transfer error. Obviously, this is difficult to achieve in pipes up to 10 cm. Installing a thermowell on a pipe elbow can provide the required immersion depth for small pipes, but this is not always possible. In addition, since the thermowell is in direct contact with the process, it was determined that any visual inspection, new installation, or replacement would require stopping the process [4].

Due to the fact that direct contact with the process is not required when measuring surface temperature in technological processes (Figure 3), some problems associated with the installation of a thermowell are partially avoided by various methods. In measurements made using this measurement method, since the measurement point is outside the medium being measured, there is no danger of physical damage or potential leakage due to internal conditions. Also, eddy current frequency calculations or other complex design calculations will not be required. However, this method also has its own drawbacks, as environmental aspects significantly affect the measurement result in the measurements made by this measurement method.



1 2 3

Figure 3. Types of surface temperature measurement sensors:

1 - welded; 2 - magnetic; 3 - clamped.

Although the traditional method of temperature measurement eliminates a number of problems and complications, in many cases, due to the accuracy of the measurement, an innovative method is required to be developed and developed. If the internal temperature of a process needs to be measured, surface temperature measurement often fails to measure the internal temperature accurately or reproducibly [12].

It has been found that external factors have a significant impact on the accuracy of surface temperature measurements, making it difficult to correlate them with process temperatures. The relationship between surface temperature and process temperature depends on the difference between the ambient temperature and the internal temperature of the process. It has been noted that even a uniform surface temperature measurement, correction, as an attempt to equalize the expected thermodynamic temperature drop in the pipe or vessel wall, cannot achieve the required accuracy when the process temperature or ambient temperature changes. It has been found that the surface temperature sensor and associated device can act as a heat sink, absorbing heat from the process or the environment, resulting in inaccuracies similar to the thermal conductivity error inherent in thermowell devices in small pipes.

In the third chapter, a model of increasing the accuracy of thermodynamic temperature measurements using an innovative method was developed, electrical characteristics were evaluated during the increase of the accuracy of thermodynamic temperature measurements using an innovative method, uncertainty in various error sources of temperature measurements performed using an innovative method was determined, and economic efficiency obtained by increasing the accuracy of thermocouples using an innovative method was determined [14, 15].

It has been known that thermocouples are widely used due to their unique and wide range of high temperature measurement capabilities during technological processes. Thermocouples produce a voltage that depends on the thermodynamic temperature as a result of the thermoelectric effect, and this voltage is widely used in temperature measurement. During the conducted research, a conventional thermometer circuit based on a thermoelectric converter was designed, a circuit with two thermoelectric converters was proposed, and possible options for evaluating the condition of these circuits during operation were considered, and an innovative method of increasing measurement accuracy was developed.

During the research carried out, a simplified and generally accepted functional scheme for measuring a thermometer based on a thermoelectric converter is shown in Figure 4. Here, MK is a microcontroller, ADC is an analog-to-digital converter, T_i is the temperature of the hot junction (measured temperature), T_s is the temperature of the cold junction.

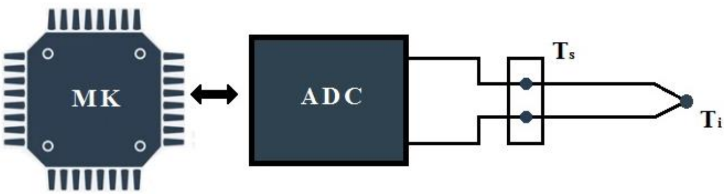


Figure 4. Functional scheme of the thermometer.

In the implemented technological processes, during operation, the cold junction of the thermocouple is either subjected to thermal stabilization, or its temperature is measured by a separate thermal transducer. At this time, the EHQ generated in the thermocouple will be equal to the potential difference at the contact point of the nodes:

$$\varepsilon(T_i, T_s) = \varepsilon_i(\mathrm{T}_i) - \varepsilon_s(\mathrm{T}_s) \quad (1)$$

Where, ε - is the thermoelectric efficiency of the thermocouple; ε_i - is the thermoelectric efficiency of the hot junction; ε_s is the thermoelectric efficiency of the cold junction.

ε(T) dependencies are defined by the IEC 60584-1:2013 standard. Functions $\varepsilon_i(\mathrm{T})$ and $\varepsilon_s(\mathrm{T})$ have the same form, they differ in independent arguments T_i and T_s. The thermoEHQ of *ε(T)* in the temperature measurement range are defined, continuous, bounded and monotonically increasing functions of a variable without discontinuities, represented by power polynomials specified in IEC 60584-1:2013. This allows to effectively solve equation (1) with respect to T_i by the simplest numerical methods. By measuring the values of the parameters *ε*, T_s and taking them into account in formula (1), any temperature T_i can be calculated[5].

As a rule, *ε(T)* is a polynomial whose degree is greater than 6, so the suitability of solving equation (1) by numerical methods has been established [16].

During the measurements, it was found that one of the most important issues is the assessment of the condition of heat exchangers during operation, which is determined by the drift of parameters or the occurrence of sensor failure. In this case, it is shown that the assessment of the situation is possible by introducing, in addition to equation (1), a relation equation of the physical quantities of the thermoelectric converter based on the partial derivatives of the thermoelectric converter with respect to the temperatures of the hot and cold junctions.

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[5] İskəndərov N.Ş. İstismar zamanı termocütlərin vəziyyətinin innovativ üsulla qiymətləndirilməsi // Azərbaycan Neft Təsərrüfatı, № 3, Bakı: - 2022, - s.38-43.

In the mentioned situation, the growth of the function $\varepsilon(T_i, T_s)$ is determined as follows:

$$\Delta\varepsilon \approx \frac{\vartheta\varepsilon}{\vartheta T_i} \cdot \Delta T_i + \frac{\vartheta\varepsilon}{\vartheta T_s} \cdot \Delta T_s \qquad (2)$$

After measuring the current values of T_i and T_s in each measurement performed, the i-th measurement is selected with the same hot junction temperature from the previous measurements:

$$T_i = T_{ii} \qquad (3)$$

Since a microcomputer is used to calculate the temperature during the measurements, and all the measurement data is saved, it is possible to find the previous measurement, which ensures the high accuracy of equation (3). In this case, it is necessary to pay attention to the fact that the temperature of the cold junctions of the current and the value chosen according to formula (3) should not coincide, that is:

$$\Delta T_s = T_s - T_{si} \neq 0 \qquad (4)$$

If we consider equations (3) and (4) in formula (2), we can obtain the following approximate equation:

$$\frac{\Delta\varepsilon}{\Delta T_s} \approx \frac{\vartheta\varepsilon}{\vartheta T_s} \qquad (5)$$

We can refine the approximate equation (5) by calculating the value of the derivative at the point T_{so} - the midpoint between T_s and T_{si}:

$$T_{so} = \frac{T_s + T_{si}}{2} \qquad (6)$$

If we consider formula (6) in formula (5), then we will get the following formula:

$$\frac{\Delta\varepsilon}{\Delta T_s} \approx \left.\frac{\vartheta\varepsilon}{\vartheta T_s}\right|_{T_s = T_{so}} \qquad (7)$$

The considered method of increasing the accuracy of numerical differentiation has been extensively described in the conducted studies. The proposed mathematical modeling method has shown itself to be quite effective within the scope of the task.

It has been found that it is usually more convenient to measure the temperature of the cold junction of a thermocouple using a resistance thermometer. Based on the current situation, it can be concluded that the temperature T_s can be considered as the correct reference point in this matter. In this regard, according to formula (7), we can determine the parameter of the metrological condition d as follows:

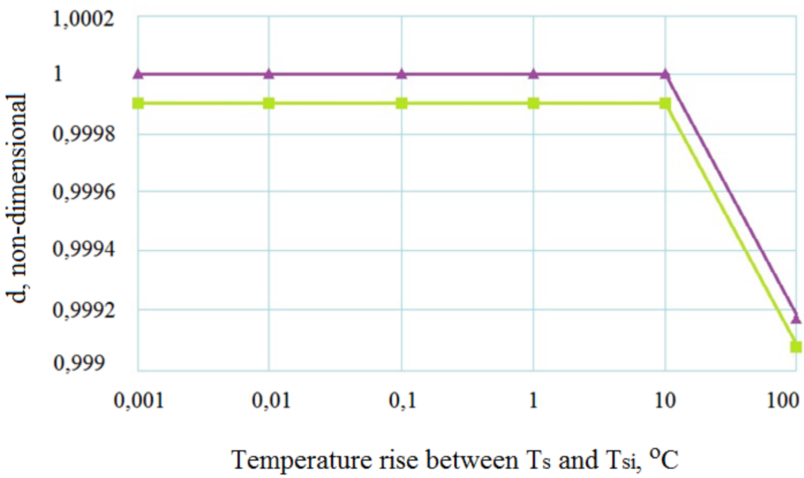
$$d = \frac{\frac{\Delta\varepsilon}{\Delta T_s}}{\left.\frac{\vartheta\varepsilon}{\vartheta T_s}\right|_{T_{so}}} \qquad (8)$$

The value of the denominator of the formula (8) is determined by the coefficients of the thermocouple polynomial (1) according to the IEC 60584-1:2013 standard and remains the same for all thermocouples of the same type. The value of the numerator is determined by the measured values of cold junction temperature and thermoEHQ. The growth of ThermoEHQ, in turn, is determined by the real coefficients of thermocouple polynomials (1). Therefore, the closeness of the value of the d parameter to the unit characterized the smallness of the measurement error of the required T_i [19].

Figure 5 shows the dependences of the d parameter on the increase of the cold junction temperature for the K-type thermocouple (chromel - alumel). The error that occurs during the measurement was simulated by selecting a random execution application according to the normal distribution law of all coefficients of the polynomial ε(T) with a RMS equal to 10^{-6}, proportional to the value of the unit mathematical expectation and the coefficient. The value for which the true temperature error value is proportional to the permissible error according to IEC 60584-1:2013 is randomly selected. The approximate value of the metrological state parameter "d" was calculated at real temperatures T_i = 800 °C, T_s = 50 °C.

It is clearly shown in Figure 5 that the selected parameter of the metrological condition "d" practically does not depend on the temperature increase between the measured current value of T_s and the selected value of T_{si} when the difference between them is less than 10 °C.

The proposed version of the condition assessment would require the use of a more efficient microcomputer in the electronics unit of the heat exchanger and an additional amount of RAM of up to hundreds of megabytes. During each measurement, ε_i – thermoEHQ, T_{ii} – measured temperature of hot junction, T_{si} – measured temperature of cold junction should be entered into RAM.



– error – 3,84 °C (allowable error 3,2 °C);

– no error.

Figure 5. Dependence of the metrological parameter "d" on the temperature rise of the cold junction.

The functional diagram of a two-thermocouple thermoelectric converter is shown in Figure 6. In the two different types of thermocouples shown here, the hot junction temperature of thermocouple 1 is the same as the hot junction temperature of thermocouple 2, and the cold junction temperature of thermocouple 1 is the same as the cold junction temperature of thermocouple 2. Unlike the previous circuit, here no temperature stabilization or measurement of the temperature at the cold junction is required.

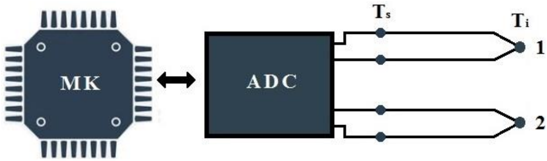


Figure 6. Functional diagram of two thermocouple thermoelectric converter.

The values of thermoelectric efficiency for both thermocouples at the temperatures T_i and T_s mentioned here can be found from the following system of equations [21]:

$$\begin{cases} \varepsilon_1(T_i, \mathrm{T}_s) = \varepsilon_{i1}(T_i) - \varepsilon_{s1}(T_s) \\ \varepsilon_2(T_i, \mathrm{T}_s) = \varepsilon_{i2}(T_i) - \varepsilon_{s2}(T_s) \end{cases} \quad (9)$$

Where ε_1, ε_2– thermoEHQ of the 1st and 2nd thermocouple; ε_{i1}, ε_{i2} – thermoEHQs of the hot junction of the 1st and 2nd thermocouples, ε_{s1}; ε_{s2} – thermoEHQs of the cold junction of the 1st and 2nd thermocouples.

It is clear that for the solution of the system of equations (9) to be possible, the following inequalities (10) must be satisfied:

$$\begin{cases} \varepsilon_1(\mathrm{T}) \neq \varepsilon_2(\mathrm{T}); \\ T_i \neq \mathrm{T}_s \end{cases} \quad (10)$$

Here, in order to carry out a successful measurement process under the conditions of measurement errors caused by noise and thermoEHQ, it is necessary to select the thermocouples with the most different dependencies ε(T) according to the IEC 60584-1 standard.

It is possible to find the solutions T_i and T_s of the system of equations (9) by the analytical method. This method reduces the problem of finding common roots of two polynomials in two variables to finding the roots of the result. However, since the terms of the polynomials included in expression (9) for traditional thermocouple types according to the IEC 60584-1:2013 standard are usually in the range of 8 to 12, in this case the resulting expression will be a determinant with dimensions ranging from 16x16 to 24x24. The elements of this determinant will again be one-variable polynomials of degree 8-12. It is clear that calculating this determinant and even finding and determining its roots in a wide range is not possible in practice. Therefore, it is more appropriate to find the unknown T_i and T_s. At this time, it was proposed to implement the temperature calculation algorithm in the form shown in Figure 7.

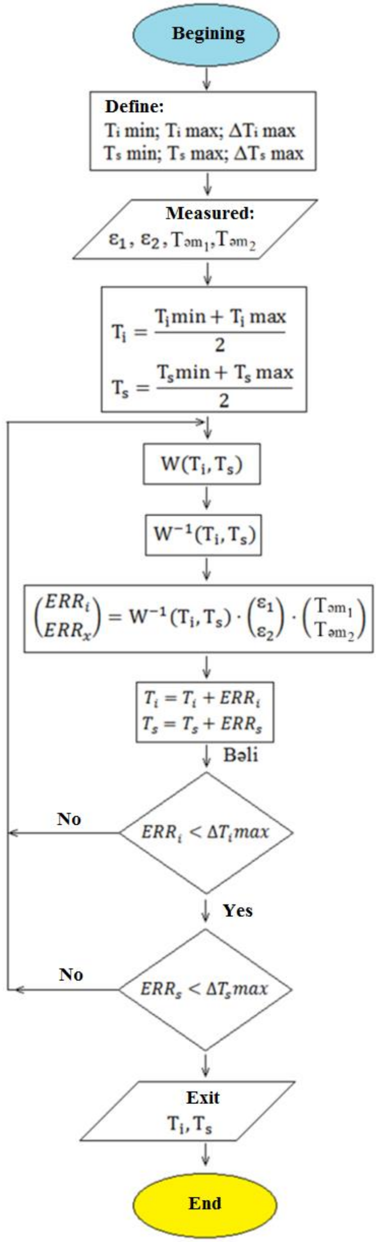


Figure 7. Algorithm for calculating temperatures of two thermocouple thermoelectric converter circuits.

In this algorithm, $T_{i\ min}$ and $T_{i\ max}$ are the limits of the temperature measurement range of the hot junction; $T_{s\ min}$, $T_{s\ max}$ – the limits of the temperature measurement range of the cold junction; $\Delta T_{i\ min}$, $\Delta T_{i\ max}$ – permissible calculated temperature errors, it is recommended to take their values 1-3 degrees less than the total permissible error of the thermometer; ε_1, ε_2 – EHQ values measured in the 1st and 2nd thermocouples; W(Ti,Ts) is the Jacobian matrix:

$$W(T_i, T_s) = \begin{pmatrix} \frac{\vartheta\varepsilon_1}{\vartheta T_i} & \frac{\vartheta\varepsilon_2}{\vartheta T_i} \\ \frac{\vartheta\varepsilon_1}{\vartheta T_s} & \frac{\vartheta\varepsilon_2}{\vartheta T_s} \end{pmatrix} \quad (11)$$

$W^{-1}(T_i, T_s)$ - inverse Jacobian matrix:

$$W^{-1}(T_i, T_s) = \frac{1}{\det W(T_i, T_s)} \begin{pmatrix} \frac{\vartheta\varepsilon_2}{\vartheta T_s} & -\frac{\vartheta\varepsilon_2}{\vartheta T_i} \\ -\frac{\vartheta\varepsilon_1}{\vartheta T_s} & \frac{\vartheta\varepsilon_1}{\vartheta T_i} \end{pmatrix}. \quad (12)$$

Where det $W(T_i, T_s)$ is the determinant of the matrix found from (11).

The issue of evaluating the state of the considered thermoelectric converter can be solved by entering the further parameter "d" of the metrological state. The assessment of the situation is possible based on the inclusion of the dependencies of the partial derivatives of the thermoelectric power of the thermocouples in the working model of the heat converter and an additional equation for connecting the physical parameters of the heat converter. At this point, it is possible to obtain the innovative metrological state parameter "d".

After measuring the current values and T_s obtained from the previous measurements, the ith measurement is selected with exactly the same cold junction temperature.

$$T_s = T_{si} \quad (13)$$

At this time, since a microcomputer is used to calculate the temperature and all measurement data is stored, it is possible to find the previous measurement that satisfies equation (13) with high accuracy. In this case, the temperatures of the hot junctions of the current and the dimensions selected according to the formula (13) should not coincide:

$$\Delta T_i = T_i - T_{ii} \neq 0 \tag{14}$$

Thus, taking into account formulas (13) and (14), formula (2) for each of the thermocouples can be written as follows:

$$\frac{\Delta\varepsilon_1}{\Delta T_i} \approx \frac{\vartheta\varepsilon_1}{\vartheta T_i} \tag{15}$$

$$\frac{\Delta\varepsilon_2}{\Delta T_i} \approx \frac{\vartheta\varepsilon_2}{\vartheta T_i} \tag{16}$$

It has been shown that if the ratio of the thermoelectric power increases of thermocouples is considered, then it can be presented in the following form:

$$\frac{\Delta\varepsilon_1}{\Delta\varepsilon_1} = \frac{\frac{\Delta\varepsilon_1}{\Delta T_i}}{\frac{\Delta\varepsilon_2}{\Delta T_i}} \approx \frac{\frac{\vartheta\varepsilon_1}{\vartheta T_i}}{\frac{\vartheta\varepsilon_2}{\vartheta T_i}} \cong \left.\frac{\frac{\vartheta\varepsilon_1}{\vartheta T}}{\frac{\vartheta\varepsilon_2}{\vartheta T}}\right|_{T=T_{io}} \tag{17}$$

Where, thermoEHQ and temperature increases are understood as the differences between their current and selected i-th measurement and T_{io} is defined similarly to the expression (6):

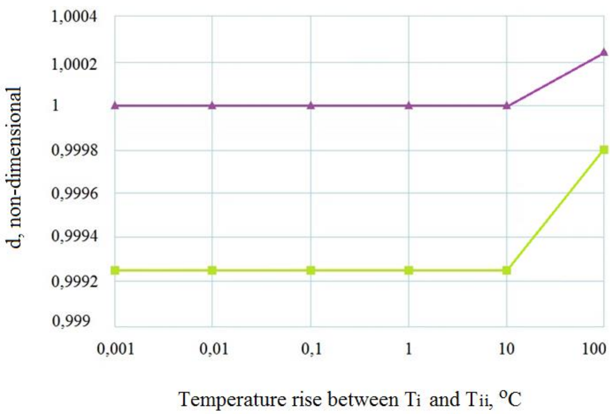
$$T_{io} = \frac{T_i + T_{ii}}{2} \tag{18}$$

At this time, based on formula (17), the following criterion for the metrological state “d” can be presented, as in formula (8):

$$d = \frac{\frac{\Delta\varepsilon_1}{\Delta\varepsilon_1}}{\left.\frac{\left(\frac{\Delta\varepsilon_1}{\Delta T_i}\right)}{\left(\frac{\Delta\varepsilon_2}{\Delta T_i}\right)}\right|_{T_i = T_{io}}} \quad (19)$$

The value of the denominator of the formula (19) is determined by the nominal coefficients of the thermocouple polynomials of the equation (9) according to the IEC 60584-1:2013 standard and is the same for all thermocouples of the same type. At this time, the value of the distributor is determined by the real coefficients of the thermocouple polynomials of equation (9). Therefore, the closeness of the "d" parameter value to the unit characterized the smallness of the measurement error of the sought value.

Figure 8 shows the dependence of the shift of the thermocouple parameters on the temperature increase of the cold junction of the criterion of the "d" metrological condition for K (chromel - alumel) and L (chromel - copel) type thermocouples.



– error – 3,17 °C (allowable error 3,2 °C);

– no error.

Figure 9. Dependence of the metrological state parameter "d" on the temperature rise of the hot junction.

At this time, the error generated in the process was simulated by choosing a random value for all coefficients of the polynomials εK(T) and εL (T) with uniform expectation and RMS equal to 10^{-6} in proportion to the value of the coefficient.

RESULTS

1. In the research work, generalized functional and structural schemes were developed in order to increase the effectiveness of the metrological support system of thermodynamic temperature measurements. Through these schemes, the main functional blocks of the system, their interaction principles and information flows were determined, and technological and methodological approaches were systematized on a scientific basis [14, 18, 20].

2. Mathematical models of the metrological support system for monitoring and controlling thermodynamic temperature parameters in technological processes were developed based on objective measurement data. The models allowed for analytical assessment of measurement accuracy based on the main variables reflecting the real conditions of the process [13, 20, 22].

3. Based on the proposed method, a systematic approach based on scientific grounds was developed for the identification and quantitative assessment of the uncertainty of the results of thermodynamic temperature measurements. This approach ensured the separation of random and systematic factors affecting the measurement process and their consideration in the uncertainty budget [16, 19, 25].

4. An innovative method has been developed to increase the accuracy of thermodynamic temperature measurements. The developed method has created a scientific and practical basis for increasing the efficiency of application in metrological practice by ensuring the stability and reliability of measurement results in complex technological conditions [11, 21].

5. As a result of experimental studies conducted on the basis of the proposed methods and models in real production conditions, the functional efficiency of the metrological assurance system has been assessed and their practical application possibilities have been developed. The results have shown that the total uncertainty range in measurement processes has decreased by 8-12 %, and the mean square error by 10-15 % [15, 23, 24].

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Personal activity of the claimant in joint works with co-authors:

[1, 2, 3, 7, 8, 9, 14, 19, 21, 22, 23, 24] - performed independently by the author.

[4, 5, 6, 10, 11, 12, 13, 11, 12, 15, 16, 17, 18, 20, 25] - were the main co-author of the work on research, analysis and processing of results.

The defense of the dissertation will be held on 17 October 2025, at 14:00, during the meeting of the One-time Dissertation Council registered under number BFD 2.02/1 at the Supreme Attestation Commission under the President of the Republic of Azerbaijan, based on the ED 2.02 Dissertation Council functioning under the Azerbaijan State Oil and Industry University (ASOIU) PLE.

Address: AZ 1010, Azadlig avenue 34, Baku, Azerbaijan,

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Electronic versions of the dissertation and its abstract is available on the official website of the "Azerbaijan State Oil and Industry University" PLE.

Abstract was sent to the required addresses on 12 September 2025.

Signed for print: 30.06.2025
Paper format: A5
Volume: 38305
Number of hard copies: 100