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Experimental temperature measurements with temperature transducers

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Abstract

The paper reviews experimental methods of temperature measurements using various types of thermometers, including liquid-glass thermometers, conductive resistance temperature transducers, and thermoelectric transducers. The principles of functioning, constructional features, working temperature ranges, and equations of resistance versus temperature are described. To improve the accuracy of measurements, methods of error correction are considered, in particular, parallax errors and incomplete immersion of the thermometer in the measuring medium, the necessity of introducing a compensation for temperature of free ends of thermocouples. The measurement procedure includes a step-by-step determination of temperature, resistance, and thermal electromotive force for conductive and thermoelectric transducers, followed by finding the temperature according to graduation tables. Examples of calculations using the procedure are described by comparing the tabulated and measured temperature values, which makes it possible to evaluate the effectiveness of using these temperature transducers when measuring certain temperatures in a thermostat. Examples of calculating the actual temperature based on the resistance of platinum and copper thermometers are provided, as well as the thermoelectric force of Chromel-Copel thermocouples.

Keywords: resistance temperature transducer; thermocouple; thermoelectric transducer; error; thermometer; graduation.

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Introduction

Temperature is a physical quantity that characterises the degree of heat in a material object. It is impossible to measure the temperature of a heated object directly, since there is no material representation of this quantity in nature, i.e. a standard measure. Therefore, to achieve temperature measurements, methods based on the determination of such properties of a substance that are unambiguously correlated with temperature and are available for measurement are used. These properties are called thermometric properties, and temperature measuring instruments are called thermometers.

The properties of objects include the volumetric and linear expansion of objects (expansion thermometers are used), the dependence of electrical resistance on temperature (resistance thermometers are used), and the occurrence of electromotive force when dissimilar metals are heated in a junction (thermoelectric thermometers are used).

In Ukraine, the principles of constructing temperature scales and methods of their implementation are regulated by the State Measurement Standard DSTU 4017-2001 [1], which is based on the International Committee for Weights and Measures' Regulations for the International Temperature Scale (ITS-90). The ITS-90 encompasses temperatures above 0.65 Kelvin, and in some of its intervals is based on fundamental physical dependencies, and in other intervals – on a series of well-established fixed points that correspond to the balance states of certain pure substances. In the intervals between the temperatures of the fixed points, interpolation is performed using formulas that determine the relationship between the measurements of reference equipment and temperature values.

The reference device that is used in a wide temperature range is a platinum resistance thermometer, the sensing element of which is made of voltage-free annealed pure platinum wire. The reference device that is used in the temperature range 630.74…1064.43 °C is a thermoelectric thermometer with electrodes made of platinum-rhodium (10% rhodium) and platinum.

1. Theoretical justifications for the measuring equipment used

Expansion thermometers

Expansion thermometers are based on the property of liquid, solid and gaseous objects to change their volume depending on heating, i.e. changes in temperature. Expansion thermometers include liquid-glass thermometers (LGTs), dilatometric, manometric, and bimetallic thermometers.

Temperature measurements using LGTs are based on the difference in the coefficients of the volume expansion between the liquid and shell material of the thermometer. Most commonly, the mercury is used as a working substance, as well as ethyl alcohol, toluene, ethyl esters. The temperature measuring range is 200 °C...1200 °C. Mercury thermometers are designed for temperatures of –30 °C... +200 °C. The advantages of LGTs, such as simplicity of use, low cost, and constant performance, have ensured their application. Measurement errors with liquid thermometers may be: 1) due to the parallax during the observer's readings; 2) due to the differences in the temperature of the measured medium and the temperature of the protruding part of a thermometer.

The first error is eliminated if the observer's eye is at the level of the liquid meniscus. To eliminate the error caused by an incomplete immersion of the thermometer in the measured medium, it is necessary to introduce a correction for the temperature on the protruding column of the thermometer by the following formula:

$$\Delta t_p = n \cdot b \cdot (t_p - t_1),$$

where n is the number of degrees on protruding column;

b is the expansion coefficient of the mercury in glass, $b = 0.00016$ (for alcohol $b = 0.001$);

t_p is the temperature indicated by thermometer;

t_1 is the ambient temperature in the laboratory at the moment of measurement, which is determined by an assisted thermometer.

In [2], the components of the systematic error in the temperature measurement using liquid thermometers are discussed in detail. The relative weight of the components varies depending on the conditions of calibration, application, and construction materials, while changing the size of thermometers improves some error components and weakens the other ones.

Resistance temperature transducers

Resistance temperature transducers use the temperature dependence of the resistance of metals and semiconductor materials. The materials used for conductive resistance temperature transducers are mainly copper and platinum, which, unlike semiconductor materials, allow for manufacturing temperature transducers with a high degree of stability and interchangeability, i.e. with the same characteristic.

According to DSTU 2858:2015 (to replace DSTU 6651:2014) [3], there are the following types of temperature transducers:

PRT is a platinum resistance thermocouple, used to measure temperatures in the range from –200 °C to +850 °C;

CRT is a copper resistance thermocouple, used to measure temperatures in the range from –50 °C to +200 °C;

NRT is a nickel resistance thermocouple, used to measure temperatures in the range from –60 °C to +180 °C.

Thermocouples function at a low current consumption, and their temperature is basically equal to the temperature of the medium. The operating current in thermocouples usually does not exceed 10...15 mA. They are made of a thin wire (50, 70, 100 μm) wound on a carcass made of electrical insulating material and placed in a metal protective enclosure furnished with fasteners and clamps for their connection to circuits.

The dependence of platinum resistance on the temperature in the range from 0 °C to +650 °C is determined by formula [4]:

$$R_t = R_0 \cdot (1 + \alpha \cdot t + \beta \cdot t^2),$$

where R_0 is a resistance at $t = 0$ °C, Ohm;

$\alpha = 3.907 \times 10^{-3}$ (1/°C);

$\beta = 5.7841 \times 10^{-7}$ (1/°C^2).

For copper resistance thermocouples, formula [4] can be used:

$$R_t = R_0 \cdot (1 + \alpha_1 \cdot t),$$

where R_0 is a resistance at $t = 0$ °C, Ohm;

$\alpha_1 = 4.26 \times 10^{-3}$ (1/°C).

Copper resistance thermocouples should be used at temperatures not exceeding 200 °C, in an atmosphere free of humidity and corrosion, as these thermocouples oxidise at higher temperatures.

Thermoelectric transducers

Thermoelectric transducers, or thermocouples, combine two non-uniform conductors connected at a single junction. The point where they are connected is called the working end of the thermocouple. Their free ends are connected to a measuring instrument.

When a working end of the thermocouple is heated, a thermal electromotive force (thermoEMF) is induced, which depends on the temperature difference between the working and free ends of the thermocouple. Thermocouples are used to measure temperatures in the range from –200 °C to +1700 °C. They are usually placed in protective steel, porcelain, or quartz tubes.

Since the temperature of free ends of the thermocouple is usually different from 0 °C in practical applications, a correction is required [5]. The correction for the temperature of free ends can be introduced by the value of the apparent thermoEMF as follows.

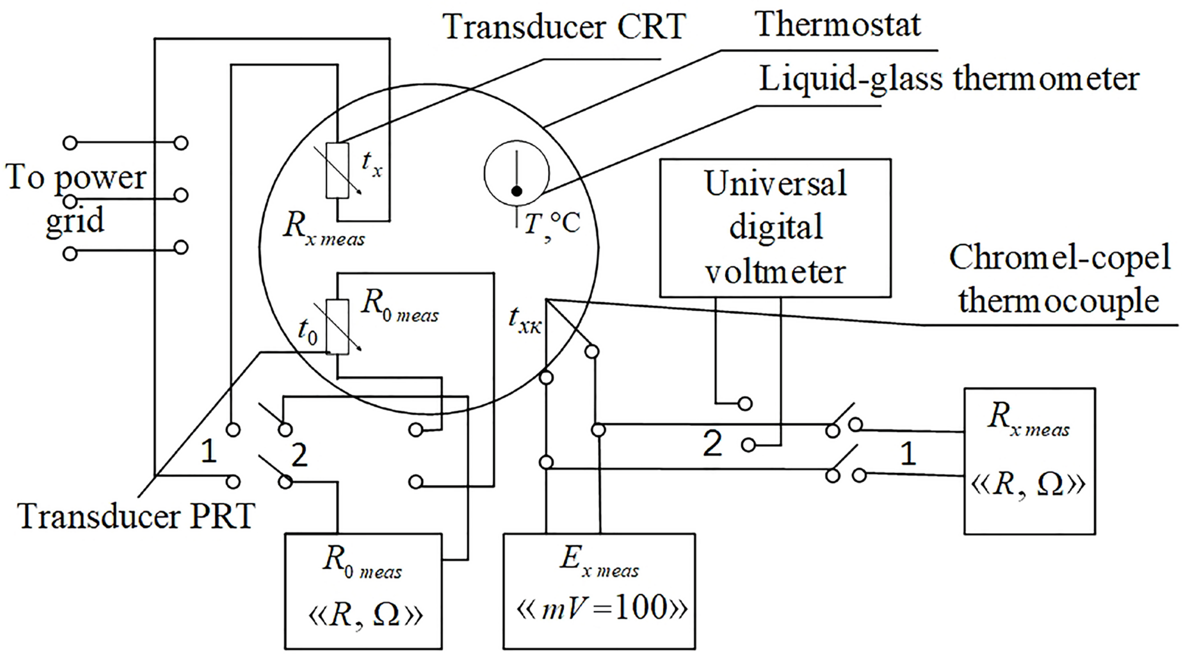

Fig. 1. Experimental measurement scheme

The measured value of the thermoEMF is at the temperature of free ends different from the graduated one (i.e., from 0 °C):

$$E = E_0 + \Delta E_K,$$

where E_0 is a thermoEMF at graduated conditions, mV;

ΔE_K is the correction for the actual temperature of free-ends, which is determined according to the tables, mV. It is considered in compliance with DSTU EN 60584-1:2016 [6].

2. Procedure for experimental measurements and evaluations

To ensure metrological traceability (MT), the results of experimental measurements were compared with the values obtained using the reference means of the measuring equipment. MT is ensured by calibrating the measuring equipment, while the established (or target, defined) accuracy of measurement results is ensured by selecting the appropriate measuring equipment, calibrating it and observing the conditions or requirements for application of measuring equipment.

In experimental measurements, MT was determined by observing the conditions of using the measuring instruments, such as resistance temperature transducers and thermocouples, which were calibrated using reference tools in accredited calibration laboratories that have the appropriate certificates for performing calibration procedures.

The measurement scheme is shown in Fig. 1. The procedure performance is ensured by:

1) Thermostat TS-16A (“ТС-16А”) (oil tank type Ts-52 (“Ц-52”); panel with clamps and outputs for connecting measuring instruments).

2) Resistance temperature transducers: copper CRT-6097 (“ТСМ-6097”), platinum 46P (“46П”); and Chromel-Copel thermocouple TCC-0515 (“ТХК-0515”).

3) Universal digital voltmeter V7-21A (“В7-21А”).

4) Liquid-glass contact thermometers (alcohol and mercury).

The procedure for implementing the measurement experiment is described below.

At first, it is necessary to set up a contact liquid-glass (mercury) thermometer included in the temperature control circuit of the thermostat. Note the reading of this liquid-glass thermometer t_p in the measurement table in accordance with the form of Table 1. Turn on the “Electric motor” switches of the thermostat. For the initial temperature of thermostat, measure the output values of temperature transducers (CRT-6097, 46P, TCC-0515), and note them in Table 1.

It should be mentioned that the resistance values of copper $R_{x\ meas}$ and platinum $R_{0\ meas}$ temperature transducers should be measured with the universal digital device V7-21A when the switch of the measured value type is set to “R, Ω”, but when the switch is set to “mV=100”, it is necessary to measure thermoEMF $E_{x\ meas}$ of thermocouple TCC-0515.

Observing the increasing readings of the contact thermometer in the thermostat during the heating of oil in the tank, it is necessary to fix the temperature values at some points alternately, switching off and on the thermostat. At these points, take the readings of the temperature transducers and note their values in Table 1.

Let us consider an example of determining the actual temperature t_0 of the thermostat from the resistance value $R_{0\ meas}$ of an exemplary platinum re-

Table 1

Table of measurements

Liquid-glass thermometer				Transducer PRT			Transducer CRT					Chromel-Copel thermocouple				
t_p	Δt_p	t_{np}	δ_p	$R_{0\ tab}$	$R_{0\ meas}$	t_0	$R_{x\ tab}$	$R_{x\ meas}$	t_x	Δt_c	δ_c	ΔE_k	$E_{x\ meas}$	$E_{x\ np}$	t_{xk}	δ_{xk}
°C	°C	°C	%	Ohm		°C	Ohm		°C	°C	%	mV	mV	mV	°C	%

Table 2

Graduation of the temperature transducer PRT

Temperature of the working end, °C	Resistance for the temperature in °C, Ohm Transducer PRT, 46 Ohm									
	0	1	2	3	4	5	6	7	8	9
10	47.82	48.01	48.19	48.37	48.55	48.73	48.91	49.09	49.28	49.46
20	49.64	49.82	50.00	50.18	50.37	50.55	50.73	50.91	51.09	51.27
30	51.45	51.63	51.81	51.99	52.18	52.36	52.54	52.72	52.90	53.08
40	53.26	53.44	53.62	53.80	53.98	54.16	54.34	54.52	54.70	54.88
50	55.06	52.24	55.42	55.60	55.78	55.96	56.14	56.32	56.50	56.58
60	56.86	57.04	57.22	57.39	57.57	57.75	57.93	58.11	58.29	58.47
70	58.65	58.83	59.00	59.18	59.36	59.54	59.72	59.90	60.07	60.25
80	60.43	60.61	60.79	60.98	61.14	61.32	61.50	61.68	61.86	62.04
90	62.81	62.39	62.52	62.74	62.92	63.10	63.28	63.45	63.63	63.81

sistance temperature transducer according to Table 2. Using the liquid-glass thermometer, the reading $t_p = 68\,°C$ was fixed. The universal voltmeter measured the reading $R_{0\ meas} = 58.06$ Ohm when the contacts were connected to the corresponding clamps of the platinum resistance temperature transducer. According to Table 2, there is a value of 58.11 Ohm that is closest to the one of $R_{0\ meas}$. The temperature marks in the Table correspond to this value as follows: horizontally "60" and vertically "7". So, $t_0 = 67\,°C$.

To determine the resistance $R_{0\ tab}$ from Table 2, which corresponds to the liquid-glass thermometer reading $t_p = 68\,°C$, proceed as Follows. In the Table, it is necessary to find a corresponding value at the intersection of horizontal marks "60" and vertical marks "8", $R_{0\ tab} = 58.29$ Ohm.

The correction Δt_p for the protruding column of mercury should also be included, and the temperature t_{np} for a liquid-glass thermometer should be determined according to the following formula:

$$t_{np} = t_p + \Delta t_p,$$

where $\Delta t_p = n \cdot 0.00016 \cdot (t_p - t_1)$;

$n = (t_p + 2)$, °C;

t_1 is the temperature determined using an auxiliary liquid-glass alcohol thermometer that is located indoors.

The relative error of measuring the temperature with a liquid-glass thermometer is determined by the following formula:

$$\delta_p = \frac{t_p - t_0}{t_0} \cdot 100\%.$$

Consider an example of determining the parameters when the contacts of the universal voltmeter are wired to the corresponding clamps of the copper resistance temperature transducer. Using the voltmeter, $R_{x\ meas} = 67.71$ Ohm was measured. According to Table 3, let us look for the closest value to $R_{x\ meas}$ (67.68 Ohm) [5]. This value corresponds to temperature marks in the Table as follows: horizontally "60" and vertically "5". So, $t_x = 65\,°C$.

When determining the resistance $R_{x\ tab}$ from Table 3, which corresponds to the reading of a liquid-glass

Table 3

Graduation of the temperature transducer CRT

Temperature of the working end, °C	Resistance for temperature in °C, Ohm Transducer CRT, 53 Ohm									
	0	1	2	3	4	5	6	7	8	9
10	55.26	55.48	55.71	55.94	56.16	56.39	56.61	56.84	57.06	57.29
20	57.52	57.74	57.97	58.19	58.42	58.64	58.87	59.10	59.32	59.55
30	59.77	60.00	60.22	60.45	60.68	60.90	61.13	61.35	61.58	61.81
40	62.03	62.26	62.48	62.71	62.93	63.16	63.39	63.61	63.84	64.06
50	64.29	64.51	64.74	64.97	65.19	65.42	65.64	65.87	66.10	66.32
60	66.55	66.77	67.00	67.22	67.45	67.68	67.90	68.13	68.35	68.58
70	68.80	69.03	69.26	69.48	69.71	69.93	70.16	70.39	70.61	70.84
80	71.06	71.29	71.51	71.74	71.97	72.19	72.42	72.64	72.87	73.09
90	73.32	73.55	73.77	74.00	74.22	74.45	74.67	74.90	75.13	75.35

thermometer, $t_p = 68\,°C$, in the Table, it is necessary to find a corresponding value at the intersection of horizontal marks "60" and vertical marks "8", $R_{x\ tab} = 68.35$ Ohm.

The absolute Δt_c and relative δ_c errors of the temperature measurement when the copper resistance temperature transducer is connected to the clamps are determined according to the following formulas:

$$\Delta t_c = t_x - t_0, \quad \delta_c = \frac{\Delta t_c}{t_0} \cdot 100\%.$$

The correction, which is determined according to Table 4 for the ambient temperature (indoor temperature) ΔE_k, is added to each measured value $E_{x\ meas}$ of the thermoEMF for the Chromel-Copel thermocouple.

For example, the indoor temperature measured with an auxiliary alcohol thermometer is 21 °C. According to Table 4, it is necessary to find a corresponding value at the intersection of horizontal marks "20" and vertical marks "1", ΔE_k =1.38 mV. When connecting the contacts of the universal voltmeter to the corresponding clamps of the Chromel-Copel thermocouple, $E_{x\ meas}$ = =2.97 mV was measured. After introducing the correction, $E_{x\ np} = E_{x\ meas} = \Delta E_k = 2.97$ mV + 1.38 mV = 4.35 mV is determined. According to Table 4, the closest value to $E_{x\ np}$(4.33 mV) is found. This value corresponds to the temperature marks "60" horizontally and "4" vertically. So, $t_{xk} = 64$ °C.

Table 4

Graduation of the Chromel-Copel thermocouple

Temperature of the working end, °C	ThermoEMF of Chromel-Copel thermocouple, mV, for temperature in °C									
	0	1	2	3	4	5	6	7	8	9
10	0.65	0.72	0.78	0.85	0.91	0.98	1.03	1.11	1.18	1.24
20	1.31	1.38	1.44	1.51	1.52	1.54	1.70	1.77	1.84	1.91
30	1.96	2.05	2.12	2.18	2.25	2.32	2.38	2.45	2.52	2.59
40	2.66	2.73	2.80	2.87	2.94	3.00	3.07	3.14	3.21	3.28
50	3.35	3.42	3.49	3.56	3.63	3.70	3.77	3.84	3.91	3.98
60	4.05	4.12	4.19	4.26	4.33	4.41	4.48	4.55	4.62	4.69
70	4.76	4.83	4.90	4.98	5.05	5.12	5.20	5.27	5.34	5.41
80	5.48	5.55	5.62	5.69	5.76	5.83	5.90	5.97	6.04	6.11
90	6.18	6.25	6.32	6.39	6.46	6.53	6.60	6.67	6.74	6.81

The relative error of the temperature measurement when being connected to the clamps of the Chromel-Copel thermocouple is determined by the following formula:

$$\delta_{xk} = \frac{t_{xk} - t_0}{t_0} \cdot 100\%.$$

Comparing the tabulated and measured values, it is possible to make conclusions about the accuracy of experimental measurements by different types of temperature transducers at the selected temperature values in the thermostat.

An important aspect for further analysis is the uncertainty evaluation of the measurement results, as well as its careful description and quantitative estimation. In the subsequent studies, it is necessary to consider in more detail an influence of systematic and random errors which are caused by various factors: deviation of the temperature of control data sets from nominal values; influence of the temperature of free ends of thermocouples; influence of external factors (among which it is needed to notice fluctuations of the ambient temperature). These factors can cause a certain level of the measurement uncertainty. Increased reliability and accuracy are achieved through a comprehensive approach to analysing every possible source of error and uncertainty, as well as using standardised procedures. This will improve the quality of experimental temperature measurements.

Conclusions

1. The procedure for performing experimental measurements and examples of parameter calculations to determine the temperatures in the thermostat using platinum, copper resistance temperature transducers and thermocouple are described. To compare the results, the appropriate graduation tables are used, which allow determining the nearest temperature value and also make it possible to estimate the accuracy of measurements by different types of temperature transducers under selected temperature conditions.

2. An important aspect that requires further research is the determination of the uncertainty components and their evaluation. The analysis of existing methods and the development of approaches to the uncertainty evaluation for temperature measurements will contribute to the improvement of the accuracy and reliability of experimental data, which is important for both scientific and applied applications. Ensuring the metrological traceability and reliability of results will improve the techniques of experimental research in the field of thermometry.

Експериментальні вимірювання температури з використанням термоперетворювачів

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Анотація

У статті розглянуто експериментальні методи вимірювання температури з використанням різних видів термометрів, включаючи рідинно-скляні, провідникові термоперетворювачі опору та термоелектричні термоперетворювачі. Особливу увагу приділено принципам роботи, детальному порядку проведення експериментальних вимірювань. Описано принципи роботи, конструктивні особливості, робочі діапазони температур, формульні залежності опору від температури. Для підвищення точності вимірювань розглянуто методи корекції похибок, зокрема похибки паралакса і неповного занурення термометра у вимірювальне середовище, необхідність введення поправки на температуру вільних кінців термопар. Склад експериментальної установки включає термостат, універсальний цифровий вольтметр, контактні рідинно-скляні термометри, мідні й платинові термоперетворювачі опору та термопару. Наведено покроковий опис експерименту: від налаштування контактного рідинно-скляного термометра до вимірювання опору термоперетворювачів та термоЕРС термопари у контрольних точках. Відзначено важливість дотримання стабільності температури та особливості підключення приладів до схеми вимірювань. Методика вимірювань передбачає поетапне визначення температури, опору, термоелектрорушійної сили для провідникових та термоелектричних термоперетворювачів, із подальшим знаходженням температури згідно з градуювальними таблицями. Описано приклади обчислень із використанням методики за допомогою порівняння табличних та виміряних значень температур, що дає змогу оцінити ефективність використання даних термоперетворювачів при вимірюванні певних температур у термостаті. Наведено приклади розрахунку дійсної температури на основі опору платинових і мідних термоперетворювачів, а також термоелектричної сили хромель-копелевих термопар. Пояснено методику врахування поправок на температуру та розрахунку абсолютних і відносних похибок для кожного типу термоперетворювачів. Результати підкреслюють важливість комплексного підходу до вимірювань, включаючи правильне налаштування обладнання, дотримання умов експерименту та ретельний аналіз похибок.

Ключові слова: термоперетворювач опору; термопара; термоелектричний перетворювач; похибка; термометр; градуювання.

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