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THE TEMPERATURE OF NANOSIZE OBJECTS. CONCEPT, DEFINITION AND MEASUREMENT

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Abstract. The concept of the temperature measurement for micro- and nanosize objects is under consideration in the proposed work. According to the decrease in the linear sizes of the controlled samples, the role and the value of fluctuations in the characteristic formation for such objects has been considered, as well as the set of metrological instruments.

Keywords: temperature measurement, nanosize objects, fluctuations, statistical thermodynamics, nanometrology.

Introduction

Nanotechnologies have not arisen at the empty place but are the natural upshot of the scientific cognition directed into the depth of a substance. Micro-, nano-dimensioned and structured materials evince new totalities of properties and functions in comparison with the bulk analogs. Research and production in this area are assured by the development of nanometrology, and first of all, the methods and means of temperature measurements, since any physical property is meaningful at some defined temperature. That is why all sorts of measurements are based on temperature monitoring, and in general temperature measurements make ~50% of a total measurement amount [1]. However, adopting the notion "temperature" for nanoobjects in contrast to macroobjects is rather problematic.

The objectives of the work are to provide the temperature support for production methods; the research and use of micro- and nano-objects at the expense of developing the methodological notions on temperature at the nano-level; the assessment of the measured temperature values due to the determined methodical, instrumental and other errors as well as uncertainties.

Methodology. The further development of nano-technologies could not be possible without the improvement in measurement methods and means of the temperature background development (**nanometrology**); data transferring and interpreting (**nanometrological supply**); the evaluation and the standard development (**standardization and certification**) and the study of properties and structures (**scientific research**).

The notion "**Temperature** of a certain **nanoobject**" has not been formed yet, although the particles under study are getting smaller every year, drawing to atoms. In general, to introduce the notion "temperature", one should consider the function of statistical distribution (a postulate of statistical physics). There are two approaches, according to which the micro-canonical or the canonical distribution must be adopted as the basis. The differences are revealed in the treating of fluctuations.

Temperature, its modes. Fluctuations and the influence of studied object size

Especially in nanometrology dealing with nanoobjects a measuring tool would detect the changes caused by fluctuations. In statistical physics, a thermodynamic system with the given temperature corresponds to two objects. The first object is a nonisolated system that interacts with a thermostat. Its temperature is supposed to be fixed; since there is a state of thermodynamic equilibrium, it is equal to the thermostat's temperature. The second object is an isolated system consisting of the set of subsystems which is equable. Its temperature as a thermodynamic parameter is the averaged inner-movement characteristic whose value could be defined with the uncertainty corresponding to small fluctuations. We deal with statistical temperature. The more atoms are present in a system, the fewer fluctuations appear. Let us highlight a principle statement of nanometry as a component of nanometrology: the presence of fluctuations makes a principle accuracy-threshold for any temperature measuring. It is predetermined by the thermal movement of the atoms of measuring instruments which consequently can not deliver absolutely exact data [2].

The case of macrothermostat (macroobject). While measuring the macroobject temperature, which is practically stable during the interaction with a thermometer (the second system), the uncertainty of the balanced temperature identification decreases with the increment of a macroobject. *In the case of microthermostat (microobject),* a notion of the fixed temperature is getting vague: the uncertainty of the measurement rises at the decrement of the quantity of atoms constituting the studied object. *The case of nanothermostat (a nanoobject).* In the system comprising the negligible quantity of matter a notion of the fixed temperature is completely absurd.

A thermodynamical notion of temperature is related to the heat exchange between two systems. The possibility of supplying or absence of the balance between them under some predetermined conditions pertains to all macroscopic systems. The necessity of describing a state of thermodynamic systems with some specific quantity becomes obvious. So the notion of **thermodynamic temperature** has been introduced for this purpose. The objective measurement of the temperature is possible due to the transitivity of the thermodynamic equilibrium. Therefore, there is a possibility of comparison of the objects temperatures without their contact. To measure temperature values one should take a system of bodies in certain states and assign them some quantitative temperature values. In such a way the *scale of temperatures* is chosen.

Temperature as a physical value characterizing the inner energy of bodies is not being measured directly nowadays. All usable means of the measurement transform temperature into some other physical value that could be used immediately. Temperature defined by the indices of a given thermometer is named **the empirical temperature** [1].

The uncertainty in description of objects by the statistical thermodynamic notion “temperature” at the diminishing of their linear sizes to a nanoarea is natural.

Devoted to developing the apparatus of statistical physics, the work [3] describes the attempts to link the term “temperature” with basic constants of microphysics on the one hand, and the threshold sizes of nanoparticles to which this notion is still applicable, on the other hand. The definition of the minimal particle size when the notion “*local temperature*” could be adopted is especially significant, i. e. the case of the temperature at which a part of thermodynamic system remains in a canonical state, and the energetic distribution of electrons corresponds to the exponentially falling one-parametric function. Nanoobjects as unequable thermodynamic systems with a slow dynamics could be described by “fluctuation dissipation temperatures”, meanwhile, in [4] the related notion of “effective temperatures” involving the values of a response and thermodynamic temperature was represented accordingly.

Problems in the measurement of nanoobjects temperature

Measurement is a process of interaction between the studied object and the thermo-sensitive substance of the thermometer which during energy exchange with the former alters its own state, to which some temperature value is then assigned (this situation is perfectly described by the measurement with a regular medical thermometer: temperature widening of mercury causes the increment of its column to some mark which acquires a temperature index). This method is indirect as the majority of known methods are.

There are 5 direct methods of thermometry: *gas, acoustic, optical, magnetic and noise*. Those methods are based on the fundamental physical laws whose mathematical descriptions consider the thermodynamic temperature (fig.1).

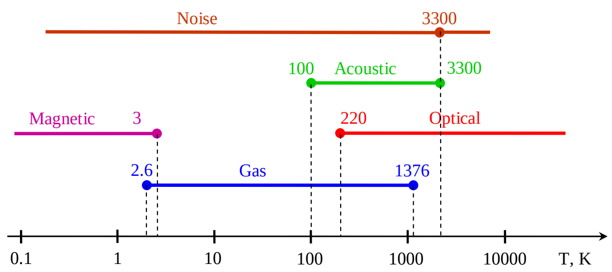

Fig.1. Temperature scales of the direct methods of thermometry

Among them, gas and optical thermometry have gained the widest application in the reproducibility of thermodynamic temperature. For instance, a random error component appears in case of the thermo capacitances, or the *dimensions*, of the thermometry-processed body and a thermometer become equal in comparison to the case when the thermo-capacitance of a thermometer is considerably less than that of a body. To determine the thermodynamic temperature of the objects within the size in the range of 100 nM ... 100 mcM, the method of the combinational dispersion of laser light [5] is used, however, considered metrological characteristics have been not elaborated enough [6]. The methods of experimental research have been improved to such an extent that it seems possible to measure temperature with the resolution below 100 nm. On the other hand, the principles of reproducing a temperature scale using melting points are altering. Due to decrease of the linear dimensions of the studied objects to nanosizes the melting temperature is not generally considered to be a stable substance characteristic [7]. It could rise or fall correspondently to the surface energy of the matter with given melting points.

The questions demanding an immediate solution arise: “What do we have to do with a thermometer when the dimensions of the thermometry-processed body decrease to nanosizes? How efficient is the switching over to nanothermometers? What is the size of micro- and nanoobjects we could study with the predetermined error by means of a nanothermometer?”

The significance of the metrological approaches to solving the nanotechnology problem. The identification of the standard characteristics at the nanolevel is related to the predetermined temperature. To measure it, the sensitivity of high-accuracy thermometers has to be improved. In the world of nanotechnology *the combination of measuring technologies and theoretical research* is getting more and more significant, since:

a) it concerns a single non repeated measurement where a classical approach of the error theory could not be applicable [8];

b) a measuring tool is getting more important; its intrusion into the energetic exchange disturbs the quantity of the studied value. Moreover, *the accuracy of measured values and that of the experimental investigations are different notions*, and the evaluation of the experimental accuracy itself implies the estimation of nanosamples as well as the selection of possible and correlated research methods.

Contrary to macroobjects where the improvement in research accuracy could be reached by the increment in the experiment extent, the improvement in measurement conditions and the minimization of outer factor influence in the case of nanoobject is of great importance. Some other relevant problems can be mentioned here: the problem of correlation between expediency and significance of instrument energetic intrusion for determination of the quantitative object characteristic; the problem of reproducibility of the research results obtained with the help of various sets of instruments applicable in this area as well as the research results obtained at different scientific centers. At the thermometry-processing of small objects a sensor (for example, a super-thin wire or laser bunch) breaks the thermodynamic equilibrium of the object so that the considerable methodical error (~27 K) appears [6].

Discussion

The task of evaluation of measurement results is of high importance today. It is quite well developed for macroobjects but it has been even not established in the case of nanosamples. General approaches are known. The extraction of a systematic error component with its own sign allows one to narrow the interval of covering a random component and serves as the basis for the formation of a cognizable component of a summary measurement error. In the most practicable case of correlation between the different components of a summary error, one should apply the IMC approach to summing the uncertainties of correlated values. In this approach the total uncertainty of the result is determined by an average quadratic value of the uncertainty of certain quantities. It reveals the possibility of simultaneous application of approaches to evaluation of errors and uncertainties corresponding to a hybrid approach to the assessment of measurement results. In other words, an error is being calculated and evaluated as a physical value, whose particular coefficients are defined with some uncertainty (fig.2) [9].

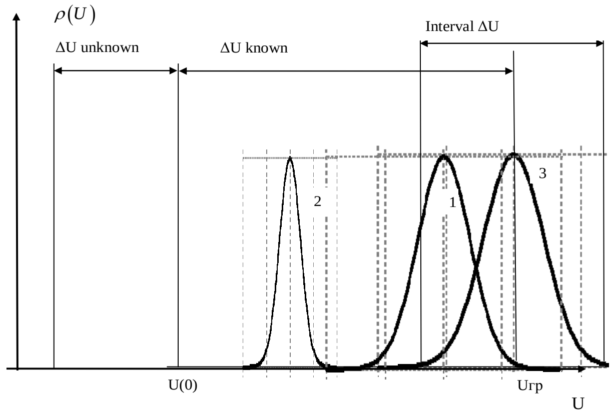

Fig.2. Threshold weight of summary error and its uncertainty (3): a systematic component due to the influence of the measurement instrument and fluctuation of its properties (2); a similar factor due to the influence of the thermometry-processed object (1)

The mentioned approach has been modified by the way of perceiving the certain components of an instrumental error through the extraction, study and evaluation of the factors influencing a measuring tool on the basis of statistical thermodynamic nature of their formation. Consequently, we have developed a hybrid thermodynamic approach to the estimation of the accuracy of micro- and nanoobjects' temperature measurement. It is based on the threshold value determination of the systematic component of the instrumental error as an additional integrity of influence-functions' multiplicative pairs.

The integrity of the pairs, where one of the multipliers is defined by the fluctuations of thermodynamic substance properties, and another is done by those of the parameters of the applied outer fields caused by the thermometry-processed object, meets the terms of the thermodynamic theorem of fluctuation dissipation. Thus firstly, the decrement of an unrecognizable error component of nanoobject temperature measurement (absolute values, covering intervals and so on) has been reached, and secondly, the fluctuation restrictions of statistical physics for the improvement of metrological characteristics have been employed [10].

Conclusions

The further development of nanotechnologies is impossible without the temperature evaluation for micro- and nanoobjects which demands the additional energetic intrusion into their life-cycle. To decrease the issues of such an intrusion, the sophisticated methods of energetic measuring influence should be developed comparing the intrusion and measurement accuracy factors on the basis of developing the fundamental notions of statistical thermodynamics concerning micro- and nanosized objects as well as the approaches to the measurement error and uncertainty.

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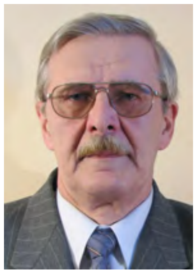

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