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Research in Nanothermometry.
Part 2: Methodical Error Problem of Contact Thermometry

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Abstract: The evaluation of temperature distortions of controlled object caused by a temperature measurement has to solve on the way of providing further nanotechnology progress. To reduce the consequences of measuring intervention to the heat balance of controlled objects, it is necessary to develop the sensitive methods of energy-measuring action. *Copyright © 2012 IFSA.*

Keywords: Temperature measurement, Micro- and nanosized objects, Related methodical error, Temperature wave.

1. Introduction

Nanotechnology has appeared due to the scientific research directed inside substance. Micro-, nanoscaled and structured materials demonstrate new set of properties and functions as compared with volumetric analogues. Their reproducible research and production are ensured by the development of nanometrology and especially by the methods and devices of temperature measurement, because each physical property has a meaning at the certain temperature. Therefore temperature control constitutes a basis for all types of measurements, and temperature measurements themselves make ~ 50 % of all measurements [1].

There are a lot of problems, which nanometrology, and especially nanothermometry, has to solve on the way of providing further progress and development of industrial production as well as applications of nanoobjects. The first of them is the elaboration of the grounds for applying concept "temperature" to nanoobjects in a similar way as to macro-objects. Enough attention has been paid to this problem recently [2-4]. The next and quite obvious problem is the evaluation of temperature distortions of the controlled object caused by a temperature measurement process , regardless of whether contact [5] or contactless [6] methods are used . Practically there are no developed methodologies and methods that could minimize the influence of a temperature measuring process of nanoobjects.

2. Aim of the Work

The aim lies in grounding a possibility to apply methods of researching temperature of micro- and nanoobjects by developing and changing methodological concepts about temperature measurements with decreasing linear dimensions of the controlled objects, and, therefore, of measuring instruments (probes) to micro- and nanoscale.

3. Metrological Model and Methodical Error of Temperature Measuring

Further evolution of nanotechnology is impossible without improving the methods and measuring devices (nanometrology) based on the development of temperature background. Every year the particles researched by scientists when approaching atoms are becoming smaller. It is accepted a priori that we do not influence the temperature field of the controlling object. This mostly happens in the case of a macroobject; since a measurement instrument is tend to be made so that its linear dimensions were one order smaller than an object. Then in case of convergence of thermo physical properties both of object and instrument, the temperature measurement with the relative methodical error $\sim 10^{-3}$ could be guaranteed. Evidently, with gradual decreasing the linear dimensions of the controlled object a point comes when further minimization of measuring instrument dimensions seems to be unreal. Usually this happens in the case of microobjects, when a measuring instrument must be 3 orders smaller in volume.

Contact methods of temperature measurement suggest that information on the status of the controlled object enters to the thermocouple sensor as a result of setting of heat exchange between them. Moreover, in the standby of thermodynamic equilibrium (with their prolonged thermal contact) the measurements are stationary, and provided short-term contact - non-stationary. In this manner we consider the conditions of the heat exchange and methodical error of temperature measurement.

As a result of prolonged thermal contact of a warm sensor and a cold controlled object, the latter is heated and the sensor is cooled, fixing the situation of a heat exchange (Fig. 1):

$$c_{ob} m_{ob} \left(T_x - T_0 \right) = c_{sen} m_{sen} \left(T_{sen} - T_x \right), \quad (1)$$

where, T_0 is the temperature of controlled object until the measurement; T_x is the temperature of controlled object, which has established due to thermal contact with the sensor; T_{sens} is the initial temperature of sensor; $c_{ob}; m_{ob}$; $c_{ob}; m_{ob}$ are the specific heat and mass of the object and the sensor respectively. In this case, the sensor measures the averaged temperature of "controlled object – sensor" in excess of $\Delta T_{met} = T_x - T_0$ the initial temperature of the first one. Expressing mass via specific density of matter w and its volume V and taking the object and the sensor uniform discoid shape (diameter $D; d$ and height $H; h$, respectively), we obtain the equation of energy balance during prolonged contact of sensor and controlled object:

$$c_{ob} w_{ob} D^2 H \Delta T_{met} = c_{sen} w_{sen} d^2 h \left(T_{sen} - T_x\right) \tag{2}$$

Dividing the left and right sides of (2) and converting it we receive a relative methodical error of measurement:

$$\delta T_{met} = \frac{c_{sen} w_{sen} V_{sen}}{c_{ob} w_{ob} V_{ob}} \left(\frac{T_{sen}}{T_x} - 1 \right) = \frac{c_{sen} w_{sen} d^2 h}{c_{ob} w_{ob} D^2 H} \left(\frac{T_{sen}}{T_x} - 1 \right), \tag{3}$$

It depends on the ratio of volume or linear dimensions of the sensor and the controlled object. Let us consider that at comparable thermal characteristics of the object and the sensor ratio of the volumes will be 1:1 (Fig. 1 a), 10:1 (Fig. 1 b) and 1:10 (Fig. 1 c). Thus, the sensor changes smoothly over time its own temperature from T_{sens} to T_x measuring the temperature of the object with a certain error.

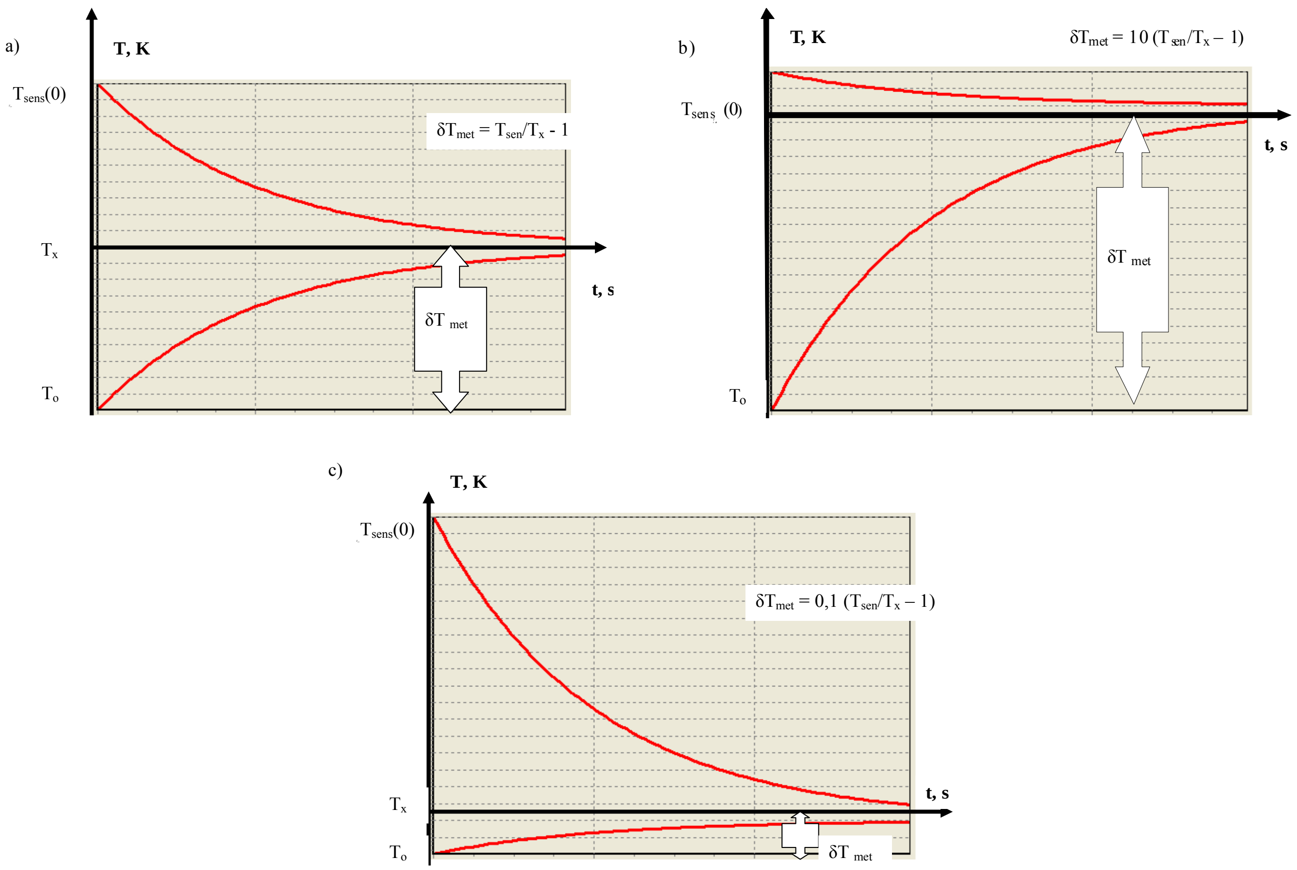

Fig. 1. Temperature vs. time changes of sensor cooling and object heating during their prolonged thermal contact:

a) $c_{ob} w_{ob} V_{ob} = c_{sen} w_{sen} V_{sen}$;

b) $10 c_{ob} w_{ob} V_{ob} = c_{sen} w_{sen} V_{sen}$;

c) $c_{ob} w_{ob} V_{ob} = 10 c_{sen} w_{sen} V_{sen}$

In the macroworld by default assume that a linear sensor size does not exceed 0.1 linear size of the controlled object, and the ratio of their volumes – 0.001. That defines a relative methodical error of measurement no higher than 0.1 %. This value loses in total other components of the measurement error, including the instrumental one. So there are grounds not to consider and not take into account the methodical error of temperature measurement.

For micro- and nano- sized sensors and controlled objects with comparable thermophysical properties (Fig. 1 b) a relative methodical error is:

$$\delta T_{met} = \frac{T_{sen}}{T_x} - 1 \tag{4}$$

For example, the temperature controlling of microobject with 270 K by means commensurate-sized sensor of initial temperature 300 K it receives $\delta T_{met} = 0{,}11 = 11\%$. This concerns methodical errors in a temperature measurement of nanoobjects with the help of nanoscaled sensors.

The temperature measuring of nanoobjects with the help of microsensors generally is not considered, as this will have methodical error of ~ 10^5 %. So, trying to use contactless the optic techniques for instance, where the beams bundle serves as a measuring probe [7]. As a consequence, there is a modified methodical error [6] due to the transfer laser bundle energy to nanoobject. The laser should work in continuous mode to ensure intensity of reflected bundle that contains temperature information. The use of biological methods [2] of temperature control brings its own restrictions and disadvantages with considerable inertia.

We can then recommend the development of non-stationary method of temperature measuring, implemented by a brief contact the sensor and the object. Thus, the equation of energy balance allows determining a relative methodical error of temperature measuring:

$$\delta T_{met} = \frac{c_{sen} w_{sen} V_{sen}}{c_{ob} w_{ob} V_{ob}} \int \frac{\partial(\Delta T_{met} / T_x)}{\partial t} dt \tag{5}$$

The short contact duration of sensor and object are determined by the structure of piezoelectric pin unit that set a duty cycle *D*. At short term contact of 10^{-3} s. (f = 1 Hz; $D = 10^{-3}$) the methodical error is corrected to the minimum comparatively the error in a stationary mode. When duration of the last is about 1 s for microobjects, the relative methodical error in non-stationary mode is ~ 10^3 less than that of stationary mode:

$$\delta T_{met.non-stat.} = D\delta T_{met.stat.} \tag{6}$$

4. Basic Theoretical Principles

The basis of mentioned non-stationary method is described below. Distribution of heat flux in an infinite thin rod is described by Fourier equation with the appropriate correction:

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial x^2} - b^2 T\,, \tag{7}$$

where t is the time; b is the constant related to boundary conditions (for its reduction the lateral thermal insulation of a rod should be applied; it is partially implemented in the designed by us equipment); a is the temperature conductivity of the material, in the concrete case, of a measurement instrument sensor. In non-stationary case, velocity of a thermal process is defined by the temperature conductivity $a = \lambda / c\rho$ (c is the heat capacity at the constant pressure; ρ is the specific density of the material), which here takes the same signification as the λ - the thermal conductivity in stationary case.

The solution of this equation that describes temperature in any moment of time and at any distance x from the contact surface is:

$$T = T_0 \exp\left(-x\sqrt{\omega/a}\right)\sin\left(\omega t - x\sqrt{\omega/a}\right), \tag{8}$$

where T_0 is the temperature of the controlled object surface; $\exp\left(-x\sqrt{\omega/a}\right)$ is the multiplier that reflects temperature reduction of sensor material with increasing distance from the contact surface; ω is the circular frequency of repeated temperature fluctuations.

By periodic contact between the surface of a rod cylindrical sensor and the flat surface of the controlled object, one-dimensional heat flux which is exposed to simple periodic temperature changes spreads in a cylinder. In the simplest case, when the controlled object is much bigger than a sensor, quite a trivial case **[**8**]** takes place, which is considered below.

Time for which the temperature reaches its maximum or minimum at any point of a sensor is determined from the equation:

$$\omega t - x\sqrt{\omega/a} = (2n+1)\frac{\pi}{2}, \tag{9}$$

Here odd values n give minimums and even maximums of a temperature wave that spreads along the normal directed from the contact surface with the certain velocity. We are interested in the case that leads to micro- and nanothermometry that takes place when thermal parameters and mass of the controlled object and sensor are commensurate. Therefore to ensure the minimal distortion of a temperature field of the controlled object, a sensor should be managed to perform only one short touch. Basing on the mentioned above, we can determine a period of time during which temperature reaches maximum at the first touch to the controlled object when $n = 2$:

$$t\big|_{n=2} = \frac{x\sqrt{\omega/a} + \frac{5\pi}{2}}{\omega}, \tag{10}$$

Through the use of a piezoelectric contact mechanism we are able to provide a repetition factor of sensor touch with the circular frequency - 20π (frequency – 10 Hz) with different discreteness. Taking a value of temperature conductivity of metal equal to 10^{-5} m^2/s, height of a sensor 2 μm and using (10), we can determine the time of temperature maximum as ~1 s.

The duration of a direct contact between sensor and object become shorter down to 10^{-3} s. using a piezoelectric unit with its duty cycle *D*. Then temperature distortion of the controlled object does not exceed 10^{-2} %, and on the other hand, an analog-digital converter (hereinafter - ADC) that is mounted on the output of a microthermometer has enough time to convert, and then to record information about the state of the object. This time value allows recording the process of passing the temperature wave through a cylindrical sensor using ADC with discreteness 10^{-5} s.

Thus, we work with the first wave of the temperature maximum in the material of a sensor, employing the above mentioned parameters, regardless of whether a sensor will or will not contact with the object. Every subsequent contact will add the following portion of heat, which spreads into the sensor substance after the first temperature wave. For the duty cycle of piezoelectric mechanism and the above mentioned dimensions of a sensor every subsequent contact occurs when the previous temperature wave has already passed through a sensor and is recorded by the ADC. Additionally it prevents us from working in an initial transition temperature mode, providing the mode of the repeated heat flux with the formed temperature wave.

5. Experimental Research

Particular attention is given to the determination of output parameters of a temperature control device, which is a part of equipment with a piezoelectric contact mechanism. The measuring instrument incorporating a sensor in the form of a tablet is mounted using the specified mechanism that allows periodically pressing a sensor to the surface of the controlled object.

At the first stage the set incorporating the thermistor in the form of a tablet with the diameter 0.2 mm and the height 2 μm is being calibrated. For this purpose we preset the value of temperature of the flat surface equal to 313 K with an error ± 0.1 K. Since the temperature conductivity of sensor material is known approximately, it is possible to define it more exactly. For this purpose we should previously calculate the average temperature of sensor material during spreading a temperature wave.

At the second stage, considering the known temperature conductivity of sensor material, it is possible to determine a temperature wave through alteration the readings of a measurement instrument in time, and thus, using (8), to calculate the temperature of the controlled object surface.

Device for measuring temperature by a brief touch of microsensors to microobject provides the temporal monitoring of temperature. In order to reduce possible damage of microobject and minimize methodical error it is purposefully limited the duration of sensor contact with object and the sensor is assigned from an object using the piezoelectric unit. Moment of feeding an electrical signal to actuator is defined as follows. According to considerable temporal discreteness of recording sensor information determine the fixed sensor data in each moment. At the same time drew from the information bank the value of probability function, tied with sensor thermal and dimensional properties [8]. Using a programmed microcontroller with the installed software of solution of two equations system with 2 temperatures for 2 temporal points of measurement, determine the microobject temperature preceding the moment of measurement.

To ensure qualitative measurements, the duty cycle of piezoelectric mechanism of measuring rod transposition is chosen so that the passing of temperature waves is fixed using ADC (the work frequency 512 kHz). As a result, the relative methodical error of temperature measurement reduces ($\sim 10^3$) concerning the relative methodical error at the prolonged contact (duration ~ 1 s.) between sensor and object, proportionally to the reducing of contact duration.

5. Conclusions

1. Further development of nanotechnology is impossible without the estimation of values of surface temperature of micro- and nanosized objects which requires additional energy intervention in a life cycle of nanoparticles. To reduce the consequences of intervention, it is necessary to develop the sensitive methods of energy-measuring action, comparing a factor of intervention with a factor of measurement accuracy on the basis of evolving the methods of temperature field analysis in the case of micro- and nanosized controlled objects and measuring instruments.
2. During the prolonged contact between sensor and controlled object, the significance of dimensions and correspondingly the estimation of controlled object temperature using a measuring instrument are related due to the ratio of their volumes (with commensurate values of their thermal conductivities)

which corresponds to the related methodical error of temperature measurements, caused by a heat transfer between object and measuring instrument. Hence, the smaller sensor of measuring instrument, the smaller relative methodical error of temperature measuring.

3. During a short (the order of milliseconds) contact between a measuring instrument and the controlled object of commensurate dimensions, the relationship between dimensions of construction parameters, including sensor thickness and its temperature conductivity, and contact duration is grounded. The reason is rooting in providing the passage of a temperature wave through the thickness of a sensor that is estimated theoretically and experimentally determined on a stage of calibrating the equipment.

References

[1]. Ya. Lutsyk, O. Huk, O. Lach, B. Stadnyk, Temperature Measurements: theory and practice, *Beskyd Bit,* Lviv, Ukraine, 2006 (in Ukrainian).

[2]. A precise nanothermometer for intracellular temperature mapping. *Nanowerk Nanotechnology Spotlight,* March 19, 2012.

[3]. V. Khanna, Frontiers of Nanosensor Technology, *Sensors and Transducers*, Vol. 103, Issue 4, 2009, pp. 1-16.

[4]. G. Gouadec, Ph. Colomban. Raman Spectroscopy of Nanomaterials: How Spectra Relate to Disorder, Particle Size and Mechanical Properties, *Progress in Crystal Growth and Characterization of Materials,* Vol. 53, Issue 1, 2007, pp. 1-56.

[5]. B. Stadnyk, S. Yatsyshyn, Thermoelectric Transducers. Investigation of Instrumental Error, *Information processing systems,* V. 79, Issue 5, 2009, pp. 106-109 (in Ukrainian).

[6]. B. Stadnyk, S. Yatsyshyn, O. Seheda. Metrology of Temperature Transducer based on Raman Effect, *Sensors and Transducers*, V. 117, Issue 6, 2010, pp. 78-84.

[7]. A. N. Magunov, Laser Thermometry of Solids, *Fizmatlit*, Moscow, 2001 (in Russian).

[8]. L. Ingersoll, O. Zobel, A. Ingersoll, Heat conduction with engineering, geological and other applications, *McGraw-Hill,* New York, 1954.

Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because of it is a peer reviewed international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per year by International Frequency Sensor Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc. Since 2011 the journal is covered and indexed (including a Scopus, Embase, Engineering Village and Reaxys) in Elsevier products.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

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