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Metrological Array of Cyber-Physical Systems. Part 15. Approach to the Creation of Temperature Standard on Basis of Fundamental Physical Constants

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Abstract: After proving the existence of Temperature Quantum the next step would be the study of possibility of Temperature Standard creation. We consider the general principles of design and operation of such advanced Temperature Standard constructed on the basis of Quantum Temperature Unit. The latter is determined solely via the fundamental physical constants. Approach to the mentioned Standard is developed in this paper. *Copyright © 2016 IFSA Publishing, S. L.*

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1. Introduction and State of Problem

Quantum standards of the most major SI units have been successfully implemented at the end of the 20th century. At this moment "Temperature" remains the last value among 7 main units of SI that is not regulated at the atomic level. Current definition of the unit of thermodynamic temperature, kelvin, is based on a material artifact, namely, the triple-point-of-water temperature [1, p.175]. The latter depends on the isotopic composition, purity etc. and therefore is not precise value, 0.01 °C.

Naturally, the efforts of world scientific community are focused on specified task, evidenced by the Program of conference TEMPMECO-2016. The recommended by Ia. Mills *et al* [2] new format of unit with new definition is the next. The kelvin, K, is the unit of thermodynamic temperature; its magnitude is set by fixing the numerical value of the Boltzmann constant to be equal to exactly 1.380 65 … $\cdot 10^{-23}$ when it is expressed in the unit $s^{-2}m^{2}kgK^{-1}$, which is equal to $J \cdot K^{-1}$. The effect of proposed definition is that the kelvin is equal to the change of thermodynamic temperature that results in a change of thermal energy k_BT by 1.380 65 … $\cdot 10^{-23}$ J/K. Then using k_B rather than T_{TPW} to define kelvin better reflects modern practice in determining thermodynamic temperature directly by primary methods, particularly at very high and low temperatures. The unit of thermodynamic temperature, the kelvin, will be redefined in 2018 by fixing the value of the Boltzmann constant, k_B. The present CODATA recommended value of k_B is determined predominantly by acoustic gas-thermometry results.

Such unilaterally concentrated solutions can lead to some success. To provide a value of k_B based on different physical principles, purely electronic measurements were performed by using a Johnson noise thermometer, by QVNS thermometry [3, Table 1 (Summary uncertainty budget for a determination of Boltzmann constant)]. Recently, "as part of these efforts, researchers from NPL's Temperature & Humidity Group have performed the most accurate determination yet of the Boltzmann constant and built an extremely accurate thermometer that measures temperature in terms of atomic motion" [4].

2. Shortcomings

This hard work, details of which have been descripting earlier, does not eliminate some principal shortcomings.

In general, the problem cannot be solved since first it is binding to the triple point of water as the main point of ITS. Second are ignored achievements of the rest of physical methods, excluding determination of Boltzmann constant. Othergates, researchers are unable to get rid of traditional calibration and only replace the outdated method by the modern one. Nevertheless, the replacement of the temperature measuring instruments for the energy ones will raise especially severe difficulties precisely in the area of ultralow energies gauging [5] that can be associated with minimal energy, or with the energy/temperature unit.

Third drawback is the lack of opportunity to take into account advances in theory of solids. Attempts of [6] to develop the concept of temperature in micro- and nanoworld may be regarded as exception. Therefore they are not considered while changing the kelvin definition.

3. Goal of the Work

Aim of work consists in researching the possibilities of creation of the built-in advanced Temperature Standard for remote complicated systems, including Cyber-Physical Systems, after implementation of concept and notion "Quantum of Temperature" in [7].

4. Temperature as a Measure of Mean Energy in the Body of Certain Dimensions

Temperature in (nano) thermometry is the statistically formed value of quantity, determined by the inner energy of a body of sufficient sizes for purpose of applying the thermodynamic consideration to this body. It seems to be one of the fittest terms among the considerable number of temperature definitions which try to identify temperature in nanothermometry. A thermodynamical notion of temperature is related to heat exchange between two systems.

Temperature as a physical value that characterizes the inner energy of bodies is not being measured directly nowadays. All usable measuring instruments transform temperature in some other physical value that could be used immediately. Temperature that is defined by indices of a thermometer of concrete type is named the empirical temperature [8].

4.1. Macro Properties and Nano Properties, Expressed by Fundamental Physical Constants. Example of Temperature

Developing the apparatus of statistical physics, try to link the term "Temperature" with basic constants of microphysics, on the one hand, and threshold sizes of nanoparticles where this notion is still applicable, on the other hand. The special significance is bestowed to the definition of the minimal particle size where the notion "local temperature" could be adopted, i. e. 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 [6]. We also have moved down the similar path [9] and successfully studied the dependence of temperature measurement trueness on the ratio of linear sizes of sensor and the measured object, while their reducing to the nanodimensions. Greater was not achieved yet.

Similarly the Boltzmann constant consideration related only to the energy of electrons scattering in process of collision with atoms may be incomplete and therefore not quite correct. While ignoring the process of acquiring energy by electrons to which may be involved in another fundamental physical constant such as Planck constant, the obtained model would be not quite perfect. These both sides of process combine a balanced approach to the problem of temperature arising as the heat manifestation (in the case of transmission of electric current through the substance) of the conduction electrons interacting with atoms. Therefore, occurrence of the Planck constant in proposed by us in [7] the Quantum Unit of Temperature becomes reasonable.

At the same time, there is another, equally effective way to study the macro properties of materials through their micro and nano properties. It is clearly indicated on the example of quantum Hall Effect research [10]. Here, a passing result have turned out in establishing the link between the macro property, expressed in 25812.807 557 ± 0.0040 ohm-resistance with the nanoscaled characteristics of the substance, which as have been proved are the charge of electron and the Planck constant. Similarly, the studies [11] have envisaged the relation of one of the based and derived electrical unit (voltage) with the same fundamental physical constants. Considering their phenomenology, we have proved to be capable

[7] the occurrence of Quantum of Temperature as the manifestation of substance's nano properties due to the electron-phonon interaction.

Normalizing the resulting characteristic to unit time, we have withdrawn the Quantum of Thermodynamic Temperature (macro property), expressed, as should be expected, in fundamental physical constants conjugated with nano properties of substance. Reduced to single electron-phonon dissipation per unit time, value is identified as **Reduced Quantum Unit of Temperature** (further RQUT):

$$\Delta T\Big|_{\substack{\Delta t\to 1s.\\ N\to 1}} = \frac{2h}{3k_B}\left[\frac{K}{s.}\right]\cdot 1[s.] \qquad (1)$$

Moreover, considering the phenomenology of these effects in conjunction with other similar phenomenon - the phenomenon of thermoelectricity, where nano properties in the form of complex of thermoelectric effects are manifested as macro quantity - integral thermopower, we can bring up to a logical end that is pertaining to the metrology. It concerns to experimental fixation of microscopic temperature changes, moreover, with minimal methodological errors. On the one hand, we get minimal, hardly noticed the change (the temperature jumps that are ~ 10^{-11} K) due to electron-phonon dissipation, and on the other hand by passing, for example, 10^8 electrons per 1 second, we obtain due to integrally expressed effect (thermo-EMF) the value, sufficient for monitoring and measurement (~ 10^{-3} K).

4.2. Metrological Conception of Quantum Unit of Temperature and Possibility of its Implementation

The given RQUT is equal to 3.199 493 $42\cdot 10^{-11}$ K with relative standard uncertainty $59.2\cdot 10^{-8}$ (defined by well-known values h and k_B of NIST tables [12]) at single electron-phonon dissipation per unit time. Since in these tables are given the uncertainties of the mentioned values, the aggregate uncertainty is estimated as $59.2\cdot 10^{-8}$. Note that these uncertainties are determined as the combined values of the set of appropriate methods. For instance, to study the Planck constant are applied the method of Watt balance, installations of studies: of X-rays crystal density, Magnetic resonance, Faraday constant, Josephson constant. CODATA 2010 recommended value of mean Planck constant relative uncertainty is only $u_h = 4.4\times 10^{-8}$.

Methods of the Boltzmann constant are the following. Constant k_B has been determined from a measurement of the sound speed in helium gas in a quasi-spherical resonator (volume 0.5 l) maintained at a temperature close to the triple point of water (273.16 K). The acoustic velocity c is deduced from measured acoustic resonance frequencies and the dimensions of the quasi-sphere, the latter being obtained via simultaneous microwave resonance [13]. An optical (laser) method for the measurement of the Boltzmann constant which reaches an uncertainty of 2×10^{-4} after a cumulative time of 61 hours is very promising [14], and other methods are considered by NIST in k_B determination.

So, the obtained value of the Boltzmann constant is determined [12] as the mean value of the row of relevant methods. Each of the last is inherent in its particular systematic constituent of error. Therefore, obtaining the mean value is not the simple issue. However, application the single, although the best method, for example the sound method, can contribute not established yet component of systematic constituent of error (or unsatisfactory trueness in the uncertainty approach). Moreover, applying this method, as the basic one, for measurement aiming the temperature determination via the value of energy, we can bring an additional error into results, since the process of temperature measurement becomes an indirect, or mediate. So, a direct measurement of T is proposed to be replaced by aforementioned one through the equation: $T = E/k_B$. By all principles of Metrology the last type of determination is always less accurate concerning the direct method's result, since its error δT is replaced in indirect method by the sum of errors: $\delta E + \delta k_B$.

Definition of 1 A = $6.2415093\cdot 10^{18}$ electrons passing through a conductor's section per 1 s. reveals that if electron pump would count 10^8 electrons per second or the precise ammeter would gauge electric current $6.24\cdot 10^{-10}$ A, we have to measure the temperature jump $3.2\cdot 10^{-11}\text{K}\cdot 10^8 = 3.2\cdot 10^{-3}$ K. This value is measurable: at sensitivity ~43 μV/K of T-type thermocouple the measured value is ~0.14 μV. The predefined uncertainty $59.2\cdot 10^{-8}$ enables to assert that the mentioned value is determined with the absolute uncertainty ~$190\cdot 10^{-11}$ K, or $1.9\cdot 10^{-9}$ K.

This is the major advantage of the advanced Temperature Standard on the basis of fundamental physical constants and its realization. Basing on a priori known value of temperature jump with the mentioned uncertainty value we can propose the extremely helpful Temperature Standard.

The researched Standard relates to the primary thermometry means. Such a declaration envisages that particular measuring instrument concerns the concrete measurand (T) which can be defined by calculating the gained results, excluding other unknown quantities and applying only fundamental physical constants as proportionality factors.

5. Investigation in Creating Temperature Standard

Our research reveals the principal opportunity and way of creating the Temperature Standard on the basis of fundamental physical constants. In this direction we have proved firstly the existence of quantization of thermodynamic temperature. So, the certain process has to take place at single electron-phonon dissipation on contacts of superconductive CNT, graphene, or another substance with quantum Hall resistance Effect. It may occur even at the room temperatures [15].

This process is independent of the set of influence factors; as deduced in our previous work [7] it depends entirely on ratio of 2 fundamental physical constants (h/k_B). Since these constants are defined with known trueness by a number of relevant methods, the Quantum of Temperature at single electron-phonon dissipation, identified as Reduced Quantum Unit of Temperature, has been deduced and determined.

5.1. Study of Advanced Temperature Standard on the Basis of RQUT

Below is discussed the possibility of researching the most contemporary measure of temperature on the basis of fundamental physical constants. For such purpose are involved the Standard of electrical resistance on the basis of Inverse of Conductance Quantum [10] as well as the Standard of Voltage based on the Josephson junctions [11], [16] that can produce voltage pulses with time-integrated areas perfectly quantized in integer values of $h/2e$ (Fig. 1). Synthesized voltage is intrinsically accurate, because it is exactly determined from the known sequence of pulses, the clock frequency f, and fundamental physical constants h and e.

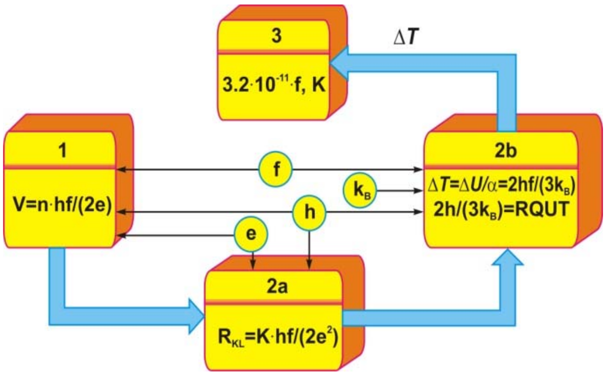

Fig. 1. Scheme of Advanced Temperature Standard on Basis of RQUT and transfer of Unit Temperature to the Working Standard: 1 is the Josephson Voltage Standard; 2a is the CNT FET; 2b is the block of adjustment; 3 is the Working Standard.

Naturally, the mentioned, very small quantity as ΔT is quite difficult to be measured. As the Standard of electrical resistance can be applied one of widespread CNT FET [17] which source and drain have to be manufactured from two dissimilar metals (for example from *Ni* and *Cu*), that constitute the built-in thermocouple via superconductive CNT quasi-junction of ~ 0.1 μm length. In such a way we obtain the possibility of measuring the temperature jump with minimal methodical error (or with maximal trueness in the uncertainty approach) and simultaneously determining the electron quantity that pass via CNT's contacts.

Thus, we consider the investigation of the electrical resistance value, which is based on the von Klitzing constant, and of the electrical voltage standard on the Josephson Effect for exact frequency-to-voltage conversion, combined with the Time Standard.

On condition of power supply from Josephson junctions array it appears an opportunity to pass a discrete particular number of electrons through nanotube of FET and to estimate the temperature jump ΔT at current I transmission (cooling is considered to be negligible).

In such a way the Reduced Quantum Unit of Temperature that is independent of kind of matter and recommended in the creation of Temperature Standard, can be regarded. It would be the Standard based on a 2 quantum effects (von Klitzing Effect and Josephson Effect) and, having been measured against the SI system of units, has a certain value with uncertainty determined by sum of 2 uncertainties: of Planck constant and of Boltzmann constant [19] which together make its total relative uncertainty value that equals to $59.2 \cdot 10^{-8}$. The last value also includes the relative standard uncertainty of atomic unit of time that is 5 orders of magnitude smaller ($5.9 \cdot 10^{-12}$ [12]) and therefore is neglected at this stage of study.

5.2. Operation Mode and Transfer of Temperature Dimension to the Working Standards

Objective measurement of temperature is possible due to the transitivity of a thermodynamic equilibrium. Therefore, we can compare the objects temperatures among themselves without the objects' per se contact.

Operating mode is as follows. The studied appliance is proposed to supply by short (~10^{-2} s.) pulse voltage consequences, effect of which is measured at the 2nd stage (power absence). Measuring temperature with minimal methodical error is easy with help of the built-in thermocouple. Superconductive CNT as the 3rd intermediate body forms a quasi-junction of thermocouple.

So, the same device serves as generator of known in advance temperature jump at the 1st stage and as Temperature measuring instrument at the 2nd stage.

Further transfer of the particular temperature jump may be realized with help of standard procedures, or better with 2nd thermocouple applying with its junction located nearby the mentioned quasi-junction. At deviation of the received signal from the signal of reference thermocouple that may be caused by heat removal, the considered signal has to be amplified to required value.

6. Conclusions

1. Due to progress in nanodimensional phenomenology that conjugates macro- and nano- properties through self-integration effects in matter, the quantization of Temperature Unit on the basis of fundamental physical constants and its implementation in Temperature Standard becomes possible. On one hand, we can get minimal, hardly fixed temperature jump (~10^{-11} K) caused by single electron-phonon dissipation; on other hand, by passing the certain amount (10^8 electrons per 1 s.), we obtain the value, sufficient for monitoring and measurement (~10^{-3} K), due to integral expressed effect (thermo-EMF).

2. Since the minimum value of temperature jump, caused by single electron-phonon dissipation per unit time, is determined via h/k_B as $3.199\ 493\ 42 \cdot 10^{-11}$ K with relative standard uncertainty $59.2 \cdot 10^{-8}$, we can apply the Temperature Standard on basis of Reduced Quantum Unit of Temperature for further transfer of Temperature unit dimension. It can be performed on Quantum Hall Resistance Standard and Josephson Voltage Standard, combined with Frequency Standard.

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