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HIGH-PRECISION TEMPERATURE MEASUREMENTS OF MATERIAL ARTIFACTS

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Abstract: Important advances in temperature measurements of material artifacts are reported as a result of a new approach in high-precision calibration of thermometers, which is free from contribution of temperature gradients in the calibration system and velocity error, associated with time delays due to propagation of heat waves in artifacts.

Keywords: velocity error, temperature gradient.

Precise temperature measurements of material artifacts are of vital importance for dimensional measurements and length metrology. For example, in Kösters interferometer [1] the uncertainty due to temperature measurement is equal to the sum of all other uncertainties of the interferometer [2]. The idea about the present state of accuracy in temperature measurements of material artifacts, that is achieved nowadays can be obtained from the results of the recent CIPM Key Comparison in length measurements CCL-K2, where the mean value of the standard deviation for 500 mm blocks was reported to be 52 nm. Using the estimate of temperature contribution in the total uncertainty [2] and the thermal expansion coefficient for steel blocks [3], we are coming to the mean temperature accuracy level of ~6 mK.

Here, a new approach in temperature measurements of material artifacts is presented, which explicitly takes into account the thermal gradients in the artifact and the velocity error in temperature measurements, associated with the propagation time of the heat waves in the artifact and the body of thermometers. The key feature of the approach is that high precision measurement of the self-heating in PRTs, that is the most delicate part of the thermometer calibration, is performed in the real experimental conditions, that is on the surface of the particular artifact. In order to detect and take into account the velocity error in thermometer calibration, the whole strategy of the temperature measurement has to be changed. It is necessary to perform synchronous measurements by two measuring channels of four parameters: two temperatures and two temperature rates are to be recorded in two areas of the artifact surface occupied by the thermometers. This procedure has to be realized several times for well-controlled heating and cooling procedures with temperature rates of about several tens of μK/minute. And the basic demand is that the propagation of the heat waves, corresponding to both heating and cooling procedures should be realized in the same direction inside the measurement set-up.

First, a few words about the origin of velocity error in temperature measurements. Typical experimental situation in temperature measurements of material artifacts with uncertainties of ~1mK is characterized by constant temperature drifts. So, in theoretical description of a system consisting of a thermometer with the time constant τ and a material block, to which this thermometer is attached, we shall assume that in the initial time moment the temperature of the thermometer T was equal to the temperature of the block T_o and then a temperature ramp, with temperature rate V, was applied to the block. The corresponding equation, describing the evolution of the system for the variable $U=(T-T_o)$ as a function of time t, can be presented in the form (1) and solution (2)

$$dU/dt = -(U - Vt)/\tau \tag{1}$$

$$T = (T_o + Vt) - \{V\tau\,(1 - \exp(-t/\tau))\} \tag{2}$$

From (2) we find, that as soon as the temperature ramp is applied to the block, the temperature of thermometer T is not equal to the temperature of the block $(T_o + Vt)$ at that moment, but is shifted from it by the value of the velocity error, given by the term in curly brackets. For $t \gg \tau$ the velocity error acquires its maximum value, equal to $(-V\tau)$.

The importance of the velocity error in temperature measurements follows from experiments performed with our double Dewar system (DDS), where aluminium temperature equalizing block was installed inside the inner Dewar and two heaters were outside it. When we placed one thermometer on the surface of the equalizing block and a SPRT inside it and realized several heating and cooling procedures in the system, we observed the peak-to-peak variation of 4 mK (Fig.1) in the temperature difference recorded by two thermometers.

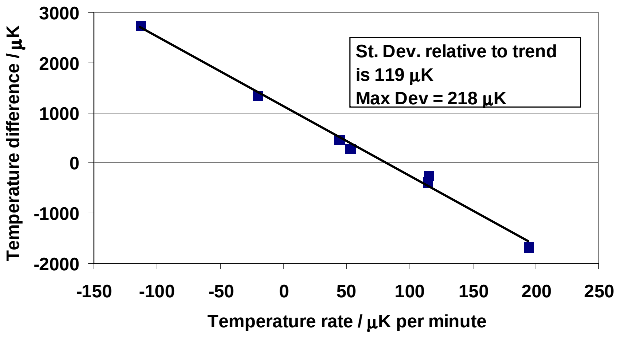

Fig.1. Velocity effect for thermometers, located at 150 mm distance.

This temperature difference was highly correlated with the sign and the rate of the temperature ramps, clearly demonstrating the velocity error effect in the calibration procedure. The maximum deviation relative to the trend in Fig.1, that describes the velocity error effect, was 0.218 mK, only. *So, when we took into account the velocity error, the 10-times improvement in calibration uncertainty was achieved for the range of temperature rates from -100 µK/minute to 200 µK/ minute.* The high level of correlation achieved in this experiment was due to the fact that the direction of the propagation of the temperature ramps was quite reproducible and it occurred in the direction along the block axis.

In the second experiment, two standard SPRTs, were installed symmetrically inside the equalizing block in separate holes filled with bath oil. The range of temperature rates was decreased to within ±55 µK/min. The “calibrated” SPRT was connected to the Guildline bridge Model 9975, and the reference thermometer was connected to ASL bridge F-18. Before this experiment, both measuring systems were calibrated in the WTP cells and in Gallium temperature standard, so that we have two realizations of the local ITS-90 temperature scales, close to 20^{o} C.

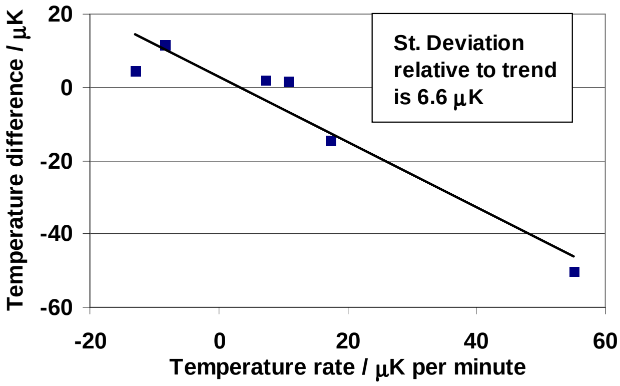

Fig.2. Velocity effect for closely installed SPRTs.

As a result of the reduced temperature rates and similar SPRTs, the observed standard deviation of the calibration results relative to calibration curve was 22.6 mcK. Still, when the residuals of the calibration were plotted as a function of the temperature rate of the reference SPRT (Fig.2), the standard deviation was further reduced to 6.6 mcK. This value is already lower than the quantization level in F18 bridge! When the described calibration procedure was repeated for the interchanged positions of the thermometers, the temperature gradient in the equalizing block was obtained (94 mcK), which was then used as a correction to obtain the final calibration relation. *This final calibration relation, which is free from velocity error and temperature gradient errors, corresponds to the condition of thermal equilibrium, which cannot be achieved experimentally.*

The effectiveness of our approach in high-precision temperature measurements of material artifacts is demonstrated by results presented in Fig.3. Here, we show measurements of the temperature of a 100-mm gauge block installed inside interferometer [4] by two independently calibrated thermometers. The upper plot shows the stability in time of the temperature at the optical axis of the gauge block when measured by a couple of thermometers, attached to the opposite narrow side surfaces of the block. After some transient process observed during the first hour of measurements, the temperature at the gauge block axis remains stable to within 1 mK during the time interval of 3 hours. Meanwhile, the agreement between the readings of two thermometers is within ±0.04 mK during half a day of measurements (including the mentioned above transient process).

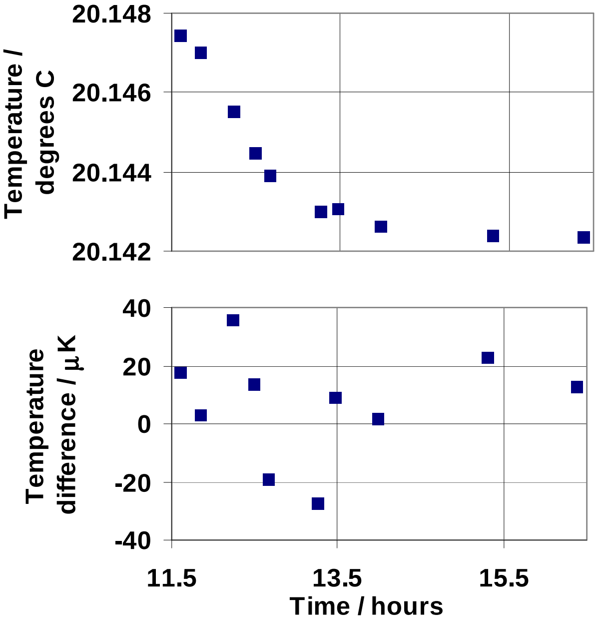

Fig.3. Stability in time of the temperature of the gauge block at its axis, when measured by two thermometers on its side surfaces (upper plot). Agreement between the temperatures, measured by two independently calibrated thermometers (lower plot).

The reproducibility of length measurements of a 100-mm steel gauge block, observed during 4 consecutive days, was found to be in picometer range (standard deviation is 36 pm). This is unprecedented result in length measurements.

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