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PRECISION MEASUREMENT OF SELF-HEATING EFFECT OF RESISTANCE THERMOMETERS INSTALLED ON MATERIAL ARTIFACTS

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Abstract: Measurement of a self-heating effect (SHE) of a platinum resistance thermometer (PRT), which is to be performed under real experimental conditions, is the trickiest part in the calibration procedure of PRTs for precise temperature measurements of material artifacts. New double-channel synchronous detection technique has been developed for precise measurement of the SHE of a resistance thermometer, located on the surface of a material artifact. With new technique, we demonstrate that a PRT modifies the temperature distribution in the artifact, and the SHE of a PRT measuring a selected point on the artifact surface, is shown to depend on the distance from the thermometer to the selected point, the heat flux conditions in the artifact, and on the temperature rate, recorded by the thermometer. New approach, based on the use of pairs of specially calibrated thermometers, which are installed at a fixed distance on the artifact surface, realizes temperature measurements of the artifact surface without temperature gradient and velocity error. The demonstrated uncertainty in temperature measurement of gauge blocks inside our interferometers is at the level below 100 µK.

Keywords: self-heating, artifact, gauge block, heat flux.

1. INTRODUCTION

Precise temperature measurements are of paramount importance for length metrology, as the dissemination of the SI length unit in all advanced countries is performed through calibration of material length standards (gauge blocks) in terms of wavelengths of standard radiations using optical interferometry. A typical resolution of a long gauge block comparator is about 4 nm [1]. For 500-mm steel gauge block, this corresponds to the temperature resolution of ~0.7 mK of that “optical thermometer”. Meanwhile, the results of the recent CIPM Key Comparisons CCL-K2 [2] show that the average uncertainty in temperature measurements of 500-mm blocks, achieved nowadays at the World leading National Metrology Institutes, is about 6 mK. This shows that the progress in high-precision temperature measurements of material artifacts will result in almost the same level of progress in the uncertainty of the dissemination of the SI length unit for the length measurements in the range of 500-1000 mm..

The advances in precise temperature measurements of material artifacts cannot be realized without improvements in calibration of platinum resistance thermometers (PRTs), which should be performed under the real experimental conditions. It means that for gauge block measurements, PRTs should be calibrated on the gauge block surfaces, including the measurement of the self-heating (SH) effect. In the first paper presented at the Congress [3], we describe the new procedure of high-precision temperature measurement, which is performed by a couple of thermometers without a contribution of temperature gradient in the experimental set-up and the velocity error. The measurements were performed with the use of two standard platinum resistance thermometers (SPRTs) in a specially designed double Dewar system (DDS). In order to find the temperature of a material artifact from the measured ratio of the resistance of the SPRT to the resistance of a temperature stabilized standard resistor, it is necessary to know the SH effect of the SPRT under the particular experimental conditions. The SH measurement is the most complicated part of the developed method of calibration of PRTs, when we measure the temperature of a particular point on the artifact surface [4], as the SH value on the artifact can be much smaller than the temperature variations of the artifact during the time interval, which is necessary to obtain the stationary temperature distribution in the artifact after the corresponding increase of the measurement current in the PRT. To overcome this problem we have developed a double-channel synchronous detection technique [4], and the application of this technique to SH measurements in DDS and on gauge block surfaces are presented in the first part of this paper. In the second part, we describe temperature measurements of gauge blocks inside INMETRO interferometers, that are realized without velocity errors and devastating effect of temperature gradients.

2. SELF-HEATING MEASUREMENTS OF PRTS INSTALLED ON ARTIFACTS

The effectiveness of our double-channel synchronous detection technique in measurements of the SH effect will be demonstrated first by experiments performed in DDS. In this case, as a result of well controlled experimental conditions [3], the obtained uncertainty in SH measurements is approaching the corresponding uncertainty of SH measurements achieved in water triple point cells. The standard procedure of SH determination, developed for temperature standards, cannot be used, as the thermometer modifies significantly the temperature regime in case of an artifact. The corresponding effect in the aluminum equalizing block of our DDS is demonstrated in Fig.1. Two SPRTs, connected to the ASL-bridge (F18) and MI-bridge (Model 6015T) were installed inside the block. At the beginning and at the end of the experiment, the currents in both thermometers were equal to 1 mA, and the block was cooling down. Then the current in ASL-bridge was changed from 1 mA to 2 mA, and the other SPRT was monitoring the block temperature. It follows from Fig.1 that there was an obvious change of the temperature regime even in a large equalizing block, when 80 µW of power were dissipated in the block as a result of current change in one of the SPRTs. To find precisely the SH value from the upper trace only is not, evidently, possible, but it is a rather easy procedure if we have an additional second channel, thus realizing a differential temperature measurement. In the developed technique for SH measurements [4], we use two reference channels equipped with thermistors and HP multy-meters. On one hand, the thermistor channels have better signal-to-noise and resolution in comparison with channels, equipped with SPRTs. On the other hand, thermistors have much smaller dimensions than SPRTs, and this of primary importance for measurements on gauge blocks.

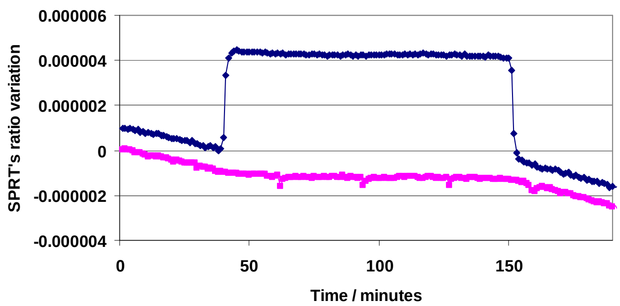
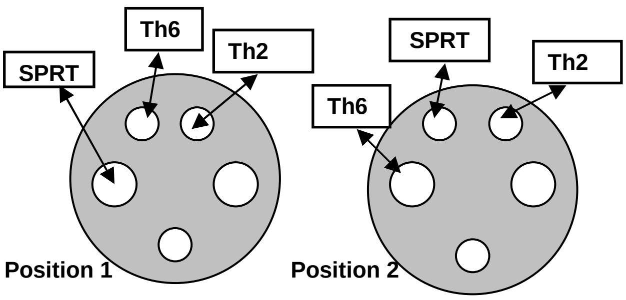


Fig.1. Variation of the temperature regime of the equalizing block in DDS with the increase of the measurement current in the SPRT.

Now we shall describe the procedure of the SH measurement for our reference SPRT in the experiments performed in DDS [3].



Position 1		Position 2	
313 µK with ref. to R2	314 µK with ref. to R6	292 µK with ref. to R2	295 µK with ref. to R6

Fig.2. Thermometers positions inside DDS and the corresponding SH values of the SPRT with reference to different sensors.

The SPRT under measurement is connected to the Guildline-bridge (Model 9975) and is run under the standard current of 1 mA, which corresponds to the absence of a signal in synchronous technique. Thermistors, designated R6 and R2 and connected to HP-multimeters 3458A, are installed in the neighboring holes of the equalizing block, filled with bath oil (Fig.2, Position 1). These systems act as reference channels, which track the temperature variations of the block. The readings of both systems are recorded simultaneously by a special computer program. For the standard current of 1 mA, the relation between the readings of the measuring and the reference channels is found in a form of linear regression dependence (regression line in Fig.3, with squares for data points). This dependence is based on the data obtained before and after the current increase to 1.41 mA. As it follows from Fig.3, a typical spread of the data points in the measurement channel relative to the linear regression line is about 3-7 µK.

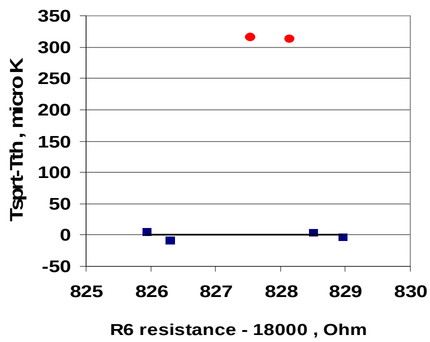
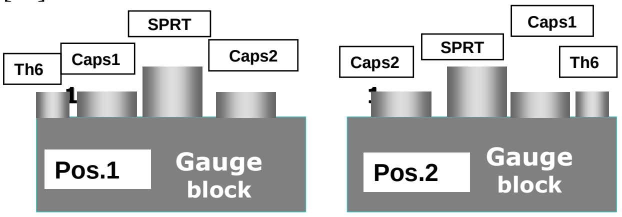


Fig.3. Self-heating measurement in DDS, using double-channel technique.

Then the current in the SPRT is increased to the value of 1.41 mA, which corresponds to the double power dissipation in the thermometer. This regime corresponds to the presence of the signal in the synchronous technique. When the stationary thermal distribution is installed in the equalizing block, (that is about 1 hour after the current increase), simultaneous measurements are performed for both channels. The difference between the recorded values in the measuring channel and the linear regression values, obtained for synchronous measurement results of the reference channel, gives the SH value for the SPRT. We present two results of the measurements of the SH effect, shown as dots in Fig.3. Each data point was obtained as a result of half an hour averaging, with the time interval between the data points of about 45 minutes. The measured values were 313.06 µK and 315.3 µK for the reference channel, equipped with thermistor R6. For the other reference with thermistor R2, the simultaneously measured SH values were 313.01 µK and 312.51 µK. The summary of the results in Position 1 is presented in Fig. 2. The comparison of these data shows that almost stationary temperature distribution in the block was realized, and the corresponding uncertainty in SH measurements was at the level of a few µK.

The developed technique is very sensitive and reflects tiny variations in the experimental set-up. For example, the SH measurements were performed for the SPRT location in the neighboring hole with the smaller diameter (10 mm in position 2, instead of 12 mm in position 1). The recorded SH value decrease was about 20 μK. At the same time, the difference between the reference channels results increased from 1 μK in position 1, to 3 μK in position 2. This was the result that the thermistor R6 was located in the wider hole in position 2.

When summarizing the results of the SH measurements in DDS, we are to remind that the temperature field variation (temperature gradient) between the locations of the SPRT in positions 1 and 2 is only a few μK [3]. Meanwhile, the SH value is about 300 μK. Under these conditions, the *propagation of the heat wave*, generated by the excessive current of 1.41 mA in the SPRT, *is highly symmetric*, as it follows from the SH results, obtained by different reference channels. This result is in strict agreement with the predictions of the existing theory of thermal conductivity [5a].



SPRT Self-Heating

Ref. to Capsule1	Ref. to Capsule2	Ref. to Therm.6	Ref. to Capsule1	Ref. to Capsule2	Ref. to Therm.6
378 μK	310 μK	421 μK	300 μK	350 μK	365 μK

Capsule1 Self-Heating

Pos. 1, Ref. to Th6	Pos.2, Ref. to Th6
250 μK	235 μK

Fig.4. Results of the first experiment on the SH measurements on the gauge block surface.

Incomparably much more difficult and interesting are the studies of SH effect performed on gauge block surfaces inside INMETRO Kösters interferometer. These studies were performed with the use of a 12-inch steel gauge block, installed inside the pressure tight aluminum chamber of the interferometer, with the wall thickness of about 200 mm. The ultra-cryostat of the interferometer was in operation, stabilizing the temperature of a copper block at the bottom of the chamber. Several thermometers were installed on the upper (narrow) side surface of the gauge block (GB), as schematically shown in Fig.4. At the center, we put our reference SPRT, which was equipped with aluminum adapter insuring a reliable thermal contact with the GB. The SPRT was connected to the Guildline-bridge. On both sides of the SPRT, we put 100 Ohm capsule PRTs (Caps.1 and Caps.2), which were connected to the most precise HP multi-meters (Model HP 3458A). The stability of the response of the multi-meters was calibrated, before and after the temperature measurement with the PRT, with the help of temperature stabilized 100 Ohm Guildline standard resistors. At the end of the GB, close to Caps.1, we put the thermistor R6, also connected to HP multy-meter. A special computer program [3,4] realized synchronous measurements of the mean temperatures and temperature rates, recorded by each sensor. We shall designate as position 1 the location of the thermometers on the gauge block, when thermistor R6 and Caps.1 are located at the left-hand side of the GB. At this end the temperature of the chamber was somewhat higher, as a result of the temperature distribution in the laboratory. The location of the sensors Caps.1 and R6 on the right hand side of the block, with the environment of lower temperature, will be called as position 2.

In the first experiment, we determined the basic parameter in these series – the spatial thermal field variation along the axis of the GB, or temperature gradient as it is often called in literature. For this we performed measurements of the temperature differences between the thermistor R6 (in positions 1 and 2) and the SPRT temperature. The value obtained was 460 μK at the whole length of the block, or 1.5 μK / mm. The left side of the block, as shown in Fig.4, had higher temperature. As the thermal conductivity through the ball suspension of the GB in the interferometer is absolutely negligible, thanks to a tiny area of the contact and a small temperature difference between the locations of the balls, the spatial variation arises due to thermal radiation of the chamber and air convection inside it. Bearing in mind the value of the temperature gradient, we are to analyze the results of SH measurements for the SPRT and Caps.1 PRT, presented in the tables of Fig.4. Comparing the SH values of the SPRT measured by Caps.1 and R6 sensors, located at different distances from the SPRT, we find that SH of the thermometer, located on the artifact surface, depends on the distance to the reference point occupied by the auxiliary thermometer. The SH value increases with distance. For example, in position 1 the SPRT SH value, with reference to R6 sensor located at the distance of 155 mm, was measured to be 421 μK, in comparison with 378 μK measured with the reference to Caps.1 at the distance of 93 mm. The increase of the SH effect with distance has a simple physical explanation: the heat wave, generated by the excessive (1.41 mA) current in the thermometer, is loosing energy, as a result of a heat exchange with the chamber, when it propagates along the artifact. The new experimental result of these studies, that is of paramount importance both for theory and experiment, is that *the propagation of the heat wave in the artifact, that is generated by the measurement current of PRT, is not symmetric, when there is a spatial temperature variation in the artifact, which amplitude is commensurable with value of the SH effect.* Thus, the gauge block with a spatial temperature variation, induced by powerful energy source with very low internal heat resistance (i.e. the interferometer chamber delivering energy to the block through thermal radiation) acts as a non-linear switch, which redistributes the energy of the heat wave (generated by thermometer) and steers more energy along the thermal flux, existing in the artifact. The asymmetry in the propagation of the heat wave, generated by the excessive current of the SPRT, was detected by all thermometers (Caps.1, Caps.2 and R6) when we changed the positions of the thermometers from 1 to 2. The effect is increasing with distance from the heat source to the reference point on the gauge block surface. This result follows from the comparison of the SH measurements, performed with R6 sensor. In case of the SPRT SH measurement, the asymmetry was about 56 μK at the mean level of 390 μK, when the distance between the centers of the thermometers was about 150 mm. Meanwhile, the asymmetry was about 15 μK at the mean level of 240 μK for the distance of ~50 mm, when we measured SH effect in Caps.1.

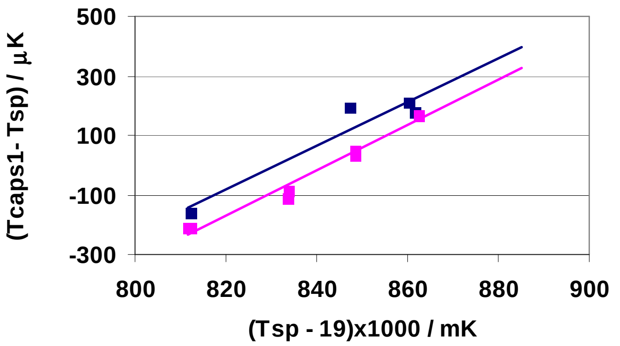


Fig.5. Demonstration of the variation in the GB temperature distribution, caused by measurement current in capsule PRT.

The other aspect of the SH problem is illustrated by Fig.5. Here we show that the energy, dissipated in the capsule PRT at the current level of 0.707 mA, is sufficient to change significantly the temperature distribution inside the gauge block. To demonstrate this, we plot the difference between the temperature of the Caps.1 PRT in position 1 and the temperature of the SPRT as a function of a fine adjustment of the ultra-cryostat stabilization temperature, which can be used for very delicate adjustment of the temperature gradient inside the GB. The data points in Fig.5 were obtained during four days, with almost stationary temperature field distribution achieved in each day of the measurement. The upper linear trend corresponds to the temperature difference between Caps.1 and the SPRT, when the other capsule PRT is switched off. The lower trend corresponds to the regime, when both capsule PRTs were in operation. When we switched on Caps.2, an additional 56 μW of power were delivered to the GB at the location of the sensor, and the arising temperature gradient in the GB resulted in the decrease of temperature difference between Caps.1 and the SPRT of about 80 μK. This is not a negligible value. Thus, the heat dissipation due to measurement current in the resistance thermometer is one of the important factors, which can limit the accuracy in temperature measurements.

The effect of asymmetric heat wave propagation in the presence of a heat flux in the artifact is so important for precise temperature measurements and for theoretical description of the heat conduction, that we performed some additional testing experiments. Again we interchanged the locations of the sensors Caps.1 and R6 on the GB surface, when measuring the SH effect of the SPRT, thus realizing the positions 1 and 2 of Fig.4. The main difference was that the PRT Caps.1 was connected to MI- bridge (6015T), realizing more accurate temperature measurements in that channel. The current value in Caps.1 was reduced to 0.5 mA, so that the heat dissipation in the sensor was only 26 μW. The PRT Caps.2 was used in a switched on mode at the current value of 0.707 mA, realizing practically symmetric type of heating of the GB surface by thermometers on it. But the results were the same: measurements of the SH value, performed with reference to the sensor located along the heat flux in the GB, were smaller, relative to the SH values obtained against the heat flux. In position 2 (for measurements along the flux), the SH values of the SPRT, obtained with reference to Caps.1 and R6, were 295 μK and 306 μK, respectively. Meanwhile, in position 1 (for measurements against the flux), the SH values were 342 μK (Caps.1 reference) and 348 μK (R6 reference).

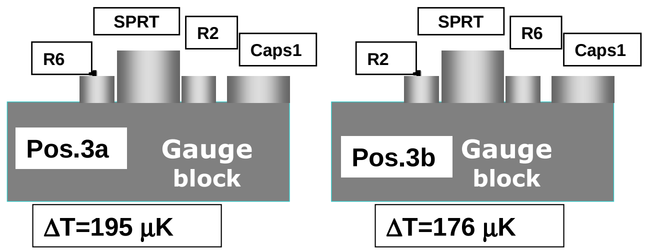


Fig.6. Results of the last experiment on the SH measurements on the gauge block surface.

In the last experiment, thermistor R6 was put close to the edge of the SPRT adapter, so that the distance between the centers of the thermometers was about 53 mm (Fig.6). Under these conditions, the time constant in the velocity error equation is below 1 minute (see Fig.4 in [6]), and the velocity error was not affecting, practically, the results of the self-heating measurement, as the temperature rates in this study were about a couple of μK / minute. Thermistor R2 was used to compensate the temperature gradient in the GB, arising due to the measurement current heat dissipation in the thermistor R6. Both thermistors were changing their positions relative to the SPRT, while PRT Caps.1 was always kept in the same position. It was connected to the MI-bridge, and monitored the stability of the conditions in both parts of the experiment. To decrease further the SH value of the SPRT, a special paste with high thermal conductivity was used to ensure better contact between the SPRT and adapter. With all these precautions, we once more detected the asymmetry in the heat wave propagation, created by the excessive measuring current in the SPRT, and the increase of the SH value with the distance to the reference point. For measurements against the heat flux, the SPRT SH value was 195 μK with reference to R6, and for measurements along the flux the SH values were 175 μK with reference to R6, and 208 μK with reference to the further located Caps1.

The discovered physical effect of asymmetric heat wave propagation inside artifact, when there is a spatial variation of the temperature field in it, makes the studies of the SH effect in a PRT to be the most complicated part of a high-precision calibration of the PRT under real experimental conditions. The SH measurement has to take into account in the explicit way:

1. Thermal interaction of an artifact with the environment, that results on the SH dependence on the distance to the reference point.
2. Spatial distribution of a thermal field inside the artifact, which redistributes the energy flux generated by the PRT, thus resulting in the dependence of the propagation parameters on the direction of propagation.
3. The velocity error effect [3], as the measurement procedure is based on the use of two thermometers on the artifact surface.

3. HIGH-PRECISION TEMPERATURE MEASUREMENTS OF GAUGE BLOCKS

Now we shall describe the procedure of precision temperature measurements of GB using calibrated thermometers. For measurements performed with the reference SPRT, we need the SH value of the thermometer determined on the GB surface inside the interferometer. The most accurate SH measurement of the SPRT is realized when we use relatively large capsule thermometer with a small measurement current and small heat dissipation (26 μW). When the capsule PRT is located at a large distance from the SPRT, then the effect of the perturbation of the temperature field by the auxiliary thermometer is diminishing. But at the large distance, the velocity error component in uncertainty of the SH measurement is giving large contribution. Besides that, the necessary requirements to the stability of the temperature gradient in the GB are very difficult to fulfill. The solution to the problem can be found in the configuration of Fig.7, where two stable SPRTs and one auxiliary sensor are located symmetrically on the artifact surface. This configuration is kept unchanged both for the calibration procedure during SH measurements and in the following temperature measurements of the GB, when optical measurements of its central length are performed. The symmetric position of SPRTs relative to the auxiliary sensor automatically cancels the effect of temperature gradient in the artifact and the effect of the velocity error for measurements of the temperature of the point, occupied by the auxiliary sensor. The effect of asymmetry of the heat wave propagation in the presence of the temperature gradient in the GB also cancels out, in the first approximation. Indeed, from Fig.6 we find that for close location of the sensor R6 relative to SPRT, the effect of asymmetry in propagation results in the SH values of 195 μK (for measurements against the heat flux) and 175 μK (for measurements along the flux), So, the variation of the SH value is ±10 μK relative to the value of 185 μK, corresponding to the zero temperature gradient in the GB. If we increase the temperature gradient by 10%, the first SH value will increase by 1 μK, and the other will decrease by the same amount (obeying the law of the energy conservation), so that the mean value will stay constant. Consequently, if we change the positions of the SPRTs relative to auxiliary sensor in Fig.7, measure the corresponding SH values for both positions, and take the mean value for each SPRT, we shall remove the effect of the propagation asymmetry from the measurement result, at least at the level of a couple of μK. If we estimate the total uncertainty in SH measurements as 10 μK (assuming it equal to whole effect of asymmetry in wave propagation of Fig.6), we shall find that the combined uncertainty in the temperature measurements of a particular point on the GB surface is about 65 μK, while the uncertainty in calibration of the SPRT in the Gallium and WTP temperature standards is around 64 μK. This example shows at what astonishing level the design of the famous Kösters interferometer has been performed from the point of view of temperature measurements.

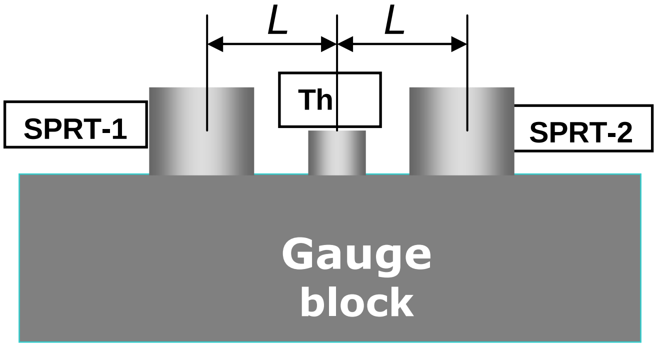


Fig.7. Thermometers configuration for precise calibration, and precise temperature measurement of a particular point on the GB surface.

Now we shall demonstrate some applications of the new methods to gauge block measurements. The experiments were performed with the primary level interferometer, used for the realization of the SI length unit in Brazil in the range of 1-100 mm [7]. In the first experiment, the longitudinal temperature variation of a 100 mm tungsten carbide (TC) block was measured, using a pair of thermistors calibrated on the GB surface and located at the opposite ends of the GB. The results of the measurements during the working day time are presented in Fig.8. The mean value is ~60 μK with the maximum deviation of 18 μK, only. For the temperature expansion coefficient of TC, this temperature gradient corresponds to the length variation of 0.24 nm, only. Thus a single thermometer, located at the center of the GB surface, gives a quite accurate result of the mean temperature value on the surface.

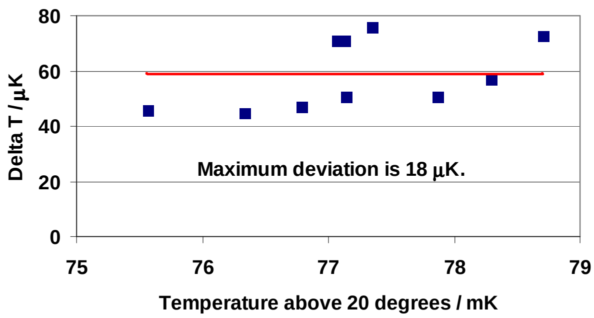


Fig.8. Measurements of an axial temperature variation on the GB surface inside interferometer.

In the next experiment, a couple of thermometers, calibrated in accordance with the described above technique, were located symmetrically at the centers of the opposite narrow side surfaces of a 100 mm steel gauge block. As discussed above, the couple of thermometers measure the temperature of the symmetrically located point between them without the velocity error, without the contribution of the temperature field variation in the vertical direction, and without the contribution of the effect of anisotropy in the thermal wave propagation in the presence of spatial temperature field distribution. Besides, this configuration realizes *mode matching* between resistance thermometry and “optical thermometer”, when both are measuring the temperature at the axis of the GB, in agreement with Abbè principle known in length measurements. The results of the measurements are presented in Fig.9.

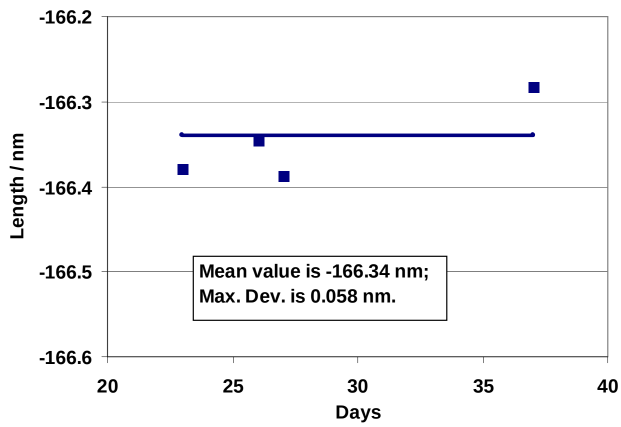


Fig.9. Demonstration of the time stability in length measurements of a 100 mm steel GB at the level of 0.058 nm.

It shows that the reproducibility of length measurements for 100 mm steel GB, observed at the time interval of a couple of weeks, was at the level of 58 pm, when characterized by the maximum deviation from the mean value. This is unprecedented result in length Metrology. The deviation of 58 pm corresponds to the agreement in indications of optical and resistance thermometers at the level of 50 μK, only.

4. CONCLUSIONS AND DISCUSSIONS

For precise SH measurements of PRTs, installed on the surface of material artifacts, we developed a new double-channel synchronous detection technique. This technique was used for the studies of the local overheating of the GB surface, resulting from the power dissipation inside the PRT. As the PRT affects the temperature distribution on the block surface, and the GB interacts through thermal radiation and air convection with the enclosure of the interferometer, the SH effect is found to depend on the distance to the reference point on the GB surface. The experiment also shows that when there is a temperature distribution inside the GB, the propagation of the heat wave, generated by the measurement current of the SPRT, becomes asymmetric, when more thermal energy propagates along the flux and less energy propagates against the flux. The developed procedure of calibration of PRTs together with the measurement technique, based on the use of a couple of thermometers calibrated under real experimental conditions, ensure temperature measurements without devastating effect of temperature gradients, velocity error, and without the effect of anisotropy in heat wave propagation.

It has been shown experimentally in this study that a SH value at the same distance from the thermometer is larger for the heat wave propagation against the heat flux in the sample, and it is smaller for measurements along the flux. This means that the amplitude damping factor, describing the decrease of the heat wave with the distance from the heat source, is larger for the measurement against the heat flux, and is smaller for the one along the flux. From the theory of thermal conductivity it follows that for periodic temperature perturbation both the velocity and the amplitude damping factor are both proportional to the square root of the frequency of the perturbation. Taking this into account, we are coming to the conclusion that experiment gives a clear indication that only high frequency Fourier components of a stepwise thermal perturbation, which have high velocity values, can propagate against the energy barrier, associated with the temperature field distribution. Meanwhile, the lowest frequency components of the heat perturbation, which are giving the main contribution to the heat transfer (See Fig.1 in [3]), cannot overcome the energy barrier and are reflected by it into the heat flux direction. Thus, in agreement with the experiment, the larger part of the energy, generated by resistance thermometer, propagates with smaller damping factors along the thermal flux, which is created by the interferometer chamber. So, we have a *non-linear device* which redistributes the thermal energy generated by the PRT. (The system is analogous to the vacuum tube, which distributes the flux of electrons when voltage signal is applied to its grid.) As it is a non-linear device, the Green function method [5a] cannot be applied: it is explicitly based on the symmetric propagation of the heat wave, and, consequently, it is not in agreement with the energy conservation principle. It follows from the presented studies that the thermal conductivity constant used in theory [5b], is in reality a tensor, showing anisotropic properties in the heat propagation, and it is a complicated function of all three coordinates, that is associated with the spatial distribution of the temperature field in the artifact. So, the ideas dealing with the presentation of the solution as a product of one-dimensional solutions are not working as a result of nonlinearity of the system. As it is explicitly emphasized in [5b], the thermal conductivity equation is based on the analysis of the result of the *steady-state experiment* of the heat propagation in a long slab. In this particular case, the thermal conductivity coefficient is, indeed, the constant. So, the results of a standard thermal conductivity theory are limited to stationary solutions and are not applicable to time-dependent processes in most of the experimental cases. Besides that, the approximation of the boundary conditions with isothermal surfaces surrounding the artifact under study is too rough for studies of the transients, when the internal heat resistance of the different sources is to be taken into account, as the heat sources are competing with each other in establishing the thermal distribution inside the artifact.

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