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ACCURATE LINEAR THERMAL EXPANSION COEFFICIENT DETERMINATION BY INTERFEROMETRY

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Abstract – In precision length measurements the accurate and traceable value of the linear thermal expansion coefficient (LTEC) is needed. A device for interferometric determination of the LTEC of gauge blocks has been constructed. Minimum temperature gradients in a gauge block with 500 mm maximum length and relatively fast operation were the objectives of this project. Based on uncertainty analysis LTEC can be measured with a standard uncertainty of $0{,}02\times10^{-6}$ 1/K for 100 mm gauge blocks.

Keywords: thermal expansion coefficient, interferometry, gauge block

1. INTRODUCTION

In length measurements, thermal expansion is a critical factor of the measurement result. Traceable determination of LTEC is an important part of accurate length measurements. In calibrations at national metrology institutes, the uncertainty of LTEC is often a major source of uncertainty. Various kinds of dilatometers have been constructed for this purpose by several metrology institutes [1, 2, 3, 4, 5]. This paper describes a dilatometer that utilises a gauge block interferometer for relative length measurement. Construction, measurement procedure and uncertainty estimation are presented.

It is commonly known that the dimensions of artefacts, like measurement standards, are dependent on temperature. Thermal expansion coefficients of metals or alloys used on length-measuring devices or standards vary on a large scale from 0 1/K (invar) to 23×10^{-6} 1/K (aluminium). The coefficient is not a constant but a function of the temperature. The coefficient is also sensitive to the composition of the material and different treatments during the process of manufacture.

The length L of an artefact at different temperatures is often estimated with the following polynomial:

$$L = L_{20} + \alpha(t-20)L_{20} + \beta(t-20)^2 L_{20} + \gamma(t-20)^3 L_{20}, \quad (1)$$

where L_{20} is the length of the artefact at normal temperature (t=20°C), α is the linear thermal expansion coefficient, β is the thermal expansion coefficient of the second order, and γ is the thermal expansion coefficient of the third order. These constants come from experimental measurements, which are fitted to the polynomial model.

When operating in a narrow temperature range near 20°C, as in most dimensional calibrations it is enough to know the linear coefficient α. The nominal length L_{nom} can be used in the correction calculations. This simplifies calculation of the length L_{20} at temperature t:

$$L_{20} = L - \alpha(t-20)L_{nom}. \quad (2)$$

Many length calibrations are mechanical comparison measurements in which the length of the artefact is determined by comparison with a reference standard of nearly the same length. In a case like this, it is commonly assumed that the temperature and LTEC of both standards are the same and that therefore no correction is needed. According to ISO 3650:1998 [6] the coefficient of thermal expansion of a steel gauge block shall be $(11{,}5\pm1{,}0)\times10^{-6}$ 1/K. This allows a maximum deviation of 2×10^{-6} 1/K in coefficients of two blocks to be compared. If temperature t of the measuring room is not 20°C, a significant error ε will emerge in the measurement result. The size of the error can be estimated with the following equation:.

$$\varepsilon_l = (\alpha_1 - \alpha_2)(t-20)L_{nom}, \quad (3)$$

where α_1 and α_2 are the thermal expansion coefficients of the gauge blocks in question. In a comparison of 100 mm long gauge blocks at temperature 20,5°C, the error is 100 nm with maximum deviation of coefficients.

2. INSTRUMENT FOR DEFINING THERMAL EXPANSION COEFFICIENT

In 2000, the Centre for Metrology and Accreditation started a project for developing a device for LTEC measurements. The objective was to make use of existing components as much as possible, and to create an instrument that has a significantly smaller uncertainty than the tolerance range given in ISO 3650:1998 [6].

2.1. General solution

The main solution is to measure the lengthening of a sample by interferometry in a vacuum. The Centre for Metrology and Accreditation has an accurate interferometric measuring instrument [7] for calibration of gauge blocks. This device is also a good basis for LTEC measurements, since it can perform fully differential measurement of

expansion. A vacuum environment was selected due to its easiness with a refractive index of medium (n) determination. If the thermal lengthening measurement were done in air, problems would likely arise in the determination of n due to large and varying temperature gradients. The problem with a vacuum solution is that thermal stabilisation times of samples are longer due to the absence of convection.

For controlled temperature change, the artefacts are placed inside a separate vacuum chamber with an isothermal radiation cavity, where the laser beam of the interferometer can be directed. Temperature control is implemented with peltier elements that are easy to regulate and have a broad range. The sample is surrounded by a copper radiation shield that closely follows the temperature changes of the peltier elements due to its good thermal conductivity. The shield forms a nearly uniform temperature around the gauge block and protects it from heat radiation from the chamber walls. The configuration of the chamber and control electronics is presented in Fig. 1.

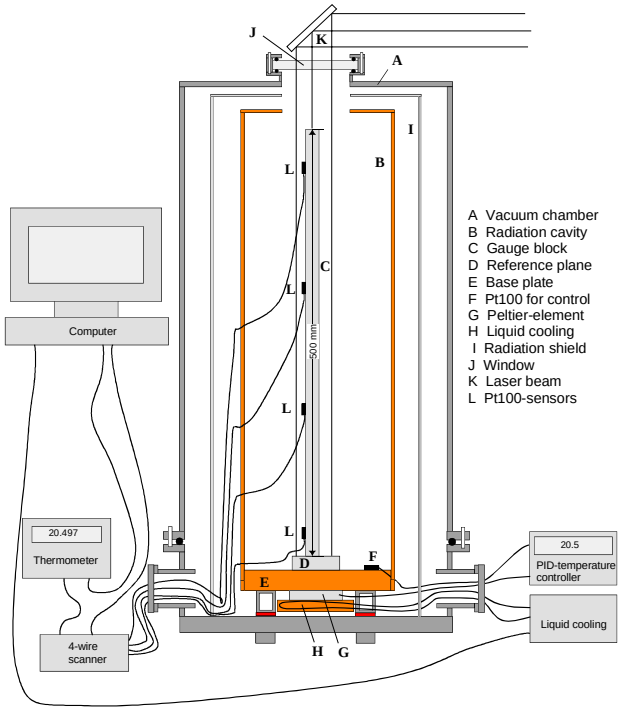

Fig. 1. Schematics of the device.

The chamber is situated next to the gauge block interferometer on a stone table. The expanded uncertainty ($k=2$) of the gauge block interferometer is $Q[10 ; 110L]$ nm. When measuring only the length expansion in a vacuum, most of the uncertainty components of the gauge block calibration are eliminated. For this purpose, the measurement program of the gauge block interferometer has been altered to record just the phase change between interference patters of the gauge block and reference platen.

2.2. Temperature control of the cavity

In order to allow fast operation and minimise temperature differences, the radiation cavity was constructed of copper (base plate 25 mm and walls 5 mm) which has an excellent thermal conductivity. The inside walls of the radiation cavity are painted a dull black to increase

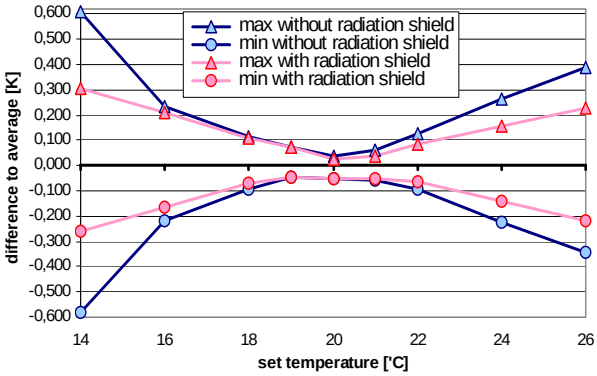

Fig. 2. Temperature differences from average temperature of the radiation cavity after 1,5 h transient time.

emissivity and therefore improve heat exchange between the cavity and the sample. On the outside it is polished and lacquered to increase reflectivity. The contact surfaces of the copper parts are greased with heat transfer paste. A radiation shield is placed between the cavity and the chamber wall. It is made of steel wire net and double radiation foil. The radiation cavity is insulated from the chamber with ceramic parts.

The temperature is set by changing the temperature of a base plate with two peltier elements. Peltier elements transfer heat to or from the plate with maximum electric power of 150 W. The other side of the peltier element is attached to a water-cooled aluminium plate. The power to the peltier elements is adjusted with a PID controller and a Pt100 sensor fixed to the plate. The stability of the controller is 2 mK. The temperature value is set by a computer program.

Temperature gradients inside the cavity were studied by connecting 4 Pt100 sensors at different heights and setting the controller from 14 to 24°C (see Fig. 2). The measurements were done with and without a radiation shield.

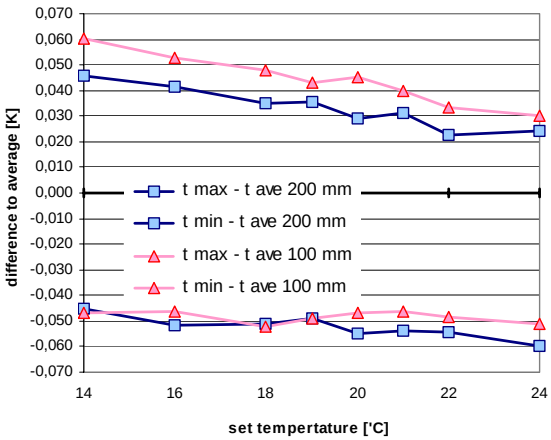

Fig. 3. Temperature differences from average temperature of the gauge block after 2 h transient time.

2.3. Measurement of sample temperature

The temperature of the sample is measured with four calibrated Pt100 sensors and a thermometer. Sensor

selection and reading is done by a 4-wire scanner and the computer. The thermometer has a resolution of 1 mK and stability of 1-2 mK/a. In order to minimise error due to non-linearity of thermometers they are calibrated in several temperatures over the operational are. Calibrations were performed in a water bath against a calibrated standard platinum resistance thermometer at 10, 15, 18, 20, 22, 25, 30 and 35°C. During LTEC measurement a correction for each sensor at the current temperature is calculated by linear interpolation. For LTEC measurement, temperature sensors are placed evenly along the gauge block.

Typical temperature gradients in a 100 mm steel gauge block are illustrated in Fig. 3. The thermal transients with the same sample are presented in Fig. 4.

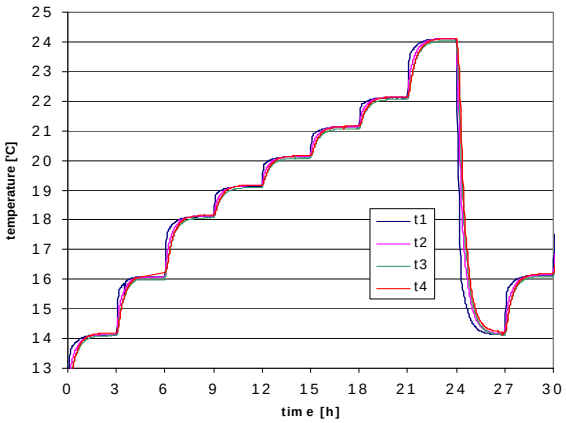

Fig. 4. Example of the settling transients of material temperature in different set-points.

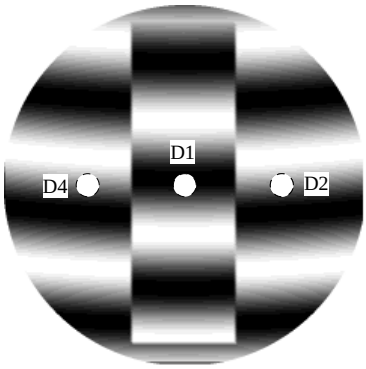

Fig. 5. Interference fringe pattern of the gauge block interferometer (simulated).

2.4. Measurement of length change

The appropriate parts of the measurement procedure of the gauge block interferometer are used for relative length measurement of the sample [5].

The interferogram of static state of the gauge block interferometer is illustrated in Fig. 5. Three photo-detectors shown as D1, D2 and D4 are used for phase difference measurement between the interference signal from the reference platen and the gauge block surfaces. For best accuracy, the length of the reference arm of the interferometer is changed by moving a large cube corner during phase difference measurement. This motion has the effect of allowing the photo-detectors to see the sinusoidal interference signal, in which one period corresponds to λ/2 change in vacuum wavelength of the reference arm. For phase difference measurement at a given temperature t_A, the signals of the three detectors are A/D-converted and phase difference from detector 1 to detectors 2 ($\varphi_{A\,1-2}$) and 4 ($\varphi_{A\,1-4}$) are calculated separately (see Fig. 6). The average gives the phase difference between the gauge block surface and the reference platen. When the temperature of the gauge block is changed to t_B the expansion alters the phase difference. The lengthening ΔL between two temperatures is determined by:

$$\Delta L = \left(\frac{\varphi_{B1-2} + \varphi_{B1-4}}{2} - \frac{\varphi_{A1-2} + \varphi_{A1-4}}{2} \right) \frac{\lambda}{4\pi} \qquad (4)$$

The non-linearity of the interferometer and phase detection algorithm is determined separately to be approximately 1 nm, expressed as standard deviation [7]. Since measurement gives only a fractional part of the phase change, it has to be repeated at proper intervals in order not to miss counts of full periods.

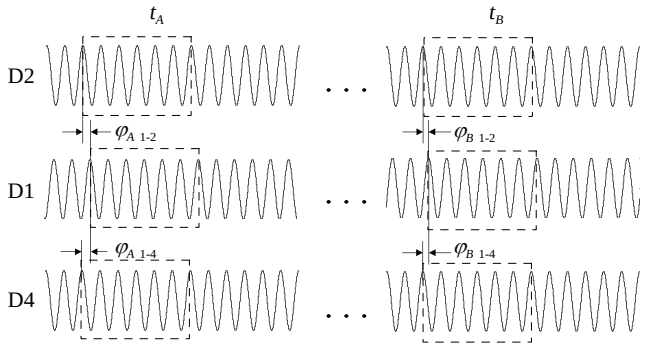

Fig. 6. A-D converted interference signals used for phase change analysis between temperatures t_A and t_B.

2.5. Procedure for LTEC measurements

The gauge block wrung to its reference platen is placed inside the chamber on the middle of the base plate so that the measuring beam can reflect properly. Some heat transfer paste is added between the gauge block base and the base plate. The sensors are uniformly pitched to the gauge block with plastic clamps. The mirror that turns the beam inside the chamber is adjusted until a suitable interference pattern is seen. The temperature is set to approach the first measuring point. When the temperature differences of sensors no longer diminish, the relative expansion is measured and recorded together with the temperature values. In LTEC calculation the average of these temperature sensor readings is used. This is repeated at suitable set points. With the chamber the LTEC can be determined in the temperature range 20±10°C. The pressure in chamber during measurement is below 2 Pa. The temperature control program monitors the reading of the gauge block temperature and controls the chamber temperature.

The LTEC α is obtained from the measurements by dividing the measured length difference ΔL by the measured

temperature difference ΔT and the nominal length L of the gauge block.

$$\alpha = \frac{1}{L}\frac{\Delta L}{\Delta T} \quad (5)$$

In normal calibration, temperature is set e.g. to 5 different values symmetrically around 20°C. The temperature is changed both to ascending and descending order and the expansion is measured. The average of results is α.

3. UNCERTAINTY

The model of LTEC measurement for analysis of the uncertainty can be expressed as follows:

$$\alpha = \frac{1}{L}\frac{\Delta L + \delta l_p}{\Delta T + \delta t_g}, \quad (6)$$

where δl_p is the correction to compensate for the non-linearity of the interferometer [7] and δt_g is the correction due to the temperature differences of the gauge block.

In defining LTEC both length and temperature measurements are differential measurements. Therefore systematic errors like curvature of the fringes of the interferometer, wringing film thickness, surface roughness difference or calibration error and self-heating of the Pt100 sensors do not affect the accuracy. The expanded uncertainty of the LTEC measurement is calculated for a 100 mm steel gauge block in Table I.

The uncertainty of the length measurement ΔL is caused by the repeatability of the phase difference measurement, which is 1 nm. That includes the laser stability.

The non-linearity of the interferometer has been investigated with a digital piezo transducer [8]. The error δl_p caused by non-linearity is estimated to have zero value with uncertainty of 1 nm.

The uncertainty of the temperature difference measurement of ΔT is composed of the repeatability and non-linearity of the temperature sensors, which is estimated to be about 4 mK. The value of correction δt_g due to temperature gradients inside the gauge block is taken as 0 mK with estimated uncertainty of 5 mK.

TABLE I. Uncertainty estimate for LTEC measurement of 100 mm steel gauge block.

Quantity	Standard uncertainty	Probability distribution	Sensitivity coefficient	Standard uncertainty $\times 10^{-6}$ 1/K
L	2 µm	normal	$-5{,}5\times10^{-5}$ m^{-1} K^{-1}	0,00011
ΔL	0,001 µm	normal	5 m^{-1} K^{-1}	0,005
δl_p	0,001 µm	rectangular	5 m^{-1} K^{-1}	0,005
ΔT	4 mK	normal	$-2{,}75\times10^{-6}$ K^{-2}	0,011
δt_g	5 mK	normal	$-2{,}75\times10^{-6}$ K^{-2}	0,014
Total				0,021

4. RESULTS

In order to test both performance and validation, several test measurements were performed. In one example, a measurement was done at 1°C intervals in the temperature range 19-21°C both ways. LTEC of $11{,}5\times10^{-6}$ 1/K for a Koba 86016 100 mm steel gauge block was previously measured by setting the laboratory room temperature. With this equipment the result value was $(11{,}48\pm0{,}04)\times10^{-6}$ 1/K.

Measurements with longer gauge blocks and of different materials will be carried out in the future. If needed the device can be modified for LTEC measurement of bulk material or ring gauges. Participation in international comparisons will also follow.

5. CONCLUSIONS

A device for determining the value of the linear thermal expansion coefficient of gauge blocks and other mirror surface artefacts was presented. This can be done with the equipment at the Centre for Metrology and Accreditation at an expanded uncertainty of $0{,}04\times10^{-6}$ 1/K (k=2).

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