REDUCTION OF UNCERTAINTY IN CALIBRATION OF GAUGE BLOCKS

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Abstract: The national standard for length in Slovenia is materialised by gauge blocks 0,5 to 1000 mm. These gauge blocks are traceable to the primary standard and are used as a reference standard for calibrating standards from industry and calibration laboratories. The best measurement capability is not comparable with the capabilities of other European national laboratories having interferometric calibration systems but is covering the industrial needs at the moment. However, our aim is to improve measurement capability without involving interferometric system which would be too expensive for the industry. Research work in this field, which is focused in critical uncertainty contributions like calibration of the equipment, as well as environmental and human influences, is represented in the article. The calibration system will be improved by reconstruction of the device and surfaces for thermal stabilisation of gauge blocks and by automation of the measurement process. Numerous experiments for analysis of thermal and human influences have already been performed and the model for diminishing these influences was established.

Keywords: measuring uncertainty, calibration, gauge blocks

1   INTRODUCTION

Involving and maintaining primary standard as National standard in Slovenia would be too expensive for Slovenian industry, because the amount of calibrations is too low. Therefore, effort is put into improving the existing secondary level. This level i can cover all the needs of the industry at the moment and can be compared with such level of calibrations in the best European accredited laboratories. National standard is realised with steel gauge blocks 0, mm to 1000 mm and calibrations of industrial standards are performed by mechanical comparison. The calibration procedure is accredited by the Dutch accreditation body RvA and by Slovenian accreditation body USM-SA. Gauge blocks representing National standards are calibrated by interferometry in different European national laboratories.

Research has shown that there are some reserves in current uncertainty budget and that the best measurement capability can be improved. The main approaches are improvement of environmental conditions and automation of the calibration procedure. The aim of this research is to reach the highest accuracy level and to be comparable with the world best laboratories.

2   UNCERTAINTY BUDGET AND CRITICAL CONTRIBUTIONS

2.1   Uncertainty budget for current conditions in the laboratory

In order to establish proper environmental conditions, special microclimatic chamber with own precise air conditioning system was built in the laboratory. Temperature deviations in the measuring space of gauge block comparator are limited to $0,1°C$. Temperature is the most important influence factor on measuring uncertainty in calibration beside the accuracy of calibration of reference gauge blocks.

The expanded uncertainty of the calibration of gauge blocks by mechanical comparison in our laboratory is currently $U = 0,05 \ \mu m + 0,5 \cdot 10^{-6} \cdot L$ using coverage factor $k = 2$. It was calculated according to EAL guide and comprises all important components. Some of them were evaluated statistically by repeated measurements, some of them were evaluated by experience and some of them on the basis of different data from manuals and calibration certificates. All the measurements including temperature measurements were performed with traceable equipment and measuring uncertainties were evaluated for all measurements.

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The uncertainty budget is shown in Table 1. However, this is only summary of the budget that is included in the gauge block calibration procedure.

Table 1. Uncertainty components in calibration of gauge blocks

Uncertainty component	current value
uncertainty of the calibration of the standard $u(l_e)$	$0.01\mu m + 0.1 \times 10^{-6} l$
uncertainty of the measured difference in lengths $u(\Delta l)$	0.016 μm
uncertainty of the thermal expansion coefficient $u(\alpha_e)$	$0{,}29 \cdot 10^{-6} \circ C^{-1}$
uncertainty in the difference in expansion coefficients $u(\delta\alpha)$	$0{,}58 \cdot 10^{-6} \circ C^{-1}$
uncertainty of the deviation of the gauge block temperature $u(\theta)$	$0{,}0534 \circ C$
uncertainty of the difference in temperatures of the gauges $u(\delta\theta)$	$0{,}0115 \circ C$

2.2   Critical contributions to the uncertainty

Critical contributions, which could be diminished, are temperature deviations, calibration of the comparator and calibration of reference gauge blocks. Temperature deviations are influenced by the air temperature deviations and by radiation of illuminating bodies and of the operator.

Temperature can not be measured on the gauge block and therefore table temperature is assumed to be the temperature of the gauge block. However, deviations between these two temperatures can differ for up to $0{,}05 \circ C$.

Additional problems appear by longer gauge blocks (near 100 mm) because temperature is not constant along the height. Beside that, thermal expansion coefficient of gauge blocks is usually not exactly known. It may differ for $1 \times 10^{-6} \circ C^{-1}$. Thermal expansion correction is therefore not accurate.

3   STRATEGY FOR DECREASING CURRENT LEVEL OF UNCERTAINTY

3.1   Study of temperature influences

The following temperature parameters have been analysed:
- change of gauge block temperature after putting it on the comparator,
- temperature difference between the gauge blocks and the comparator table,
- temperature influence of the illumination and the operator, and
- thermal expansion coefficients of gauge blocks.

All the above parameters were detected as critical and are therefore subject of optimisation.

Research was focused into experimental simulations of different materials and colours of these materials. It was found out that the radiation of different materials is quite different and that calibration results are critically influenced by radiation. The first resource of radiation are lights producing constant radiation that can be eliminated from calibration result by calculation. The second source of radiation is the operator. This source is not constant and is quite critical because the gauge block that is closer to the operator is heated stronger that the gauge block standing behind the first one. Shield that is put between the operator and the comparator is made of transparent plastics in order to enable the operator to look into measuring area. However, the isolating properties of this material are not good enough to stop the radiation of a human body.

3.2   Surfaces for thermal stabilisation of the gauge blocks

Surfaces for thermal stabilisation of gauge blocks have a great influence on thermal behaviour of gauge blocks during the calibration. If these surfaces get other temperature than the air and the comparator table, the gauge block temperature changes rapidly Our analyses have shown that an aluminium plate with bright shining or light grey surface gives the best results. Long term temperature measurements are shown in Figure 1 as an example. The white plastic surfaces used before these studies are always warmer than the air and cause additional heating of gauge blocks. The same properties have steel surfaces. The stone that has been used in the past has the worst characteristics and is not recommended at all.

In this research four materials (aluminium, steel, stone and plastic) in four different colours (black, white, grey and shining) were tested. Temperature was measured in the air, on the tested surface and on the gauge blocks, that were put on these surfaces. Long term and short term deviations were

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measured with the light turned on and with the light turned off in the measurement room. When the light was turned off, the differences were not so critical because the radiation was very low. In contrary, when the lights were turned on, big differences in temperature changes were observed. The worst behaviour was detected at dark steel and stone surfaces.
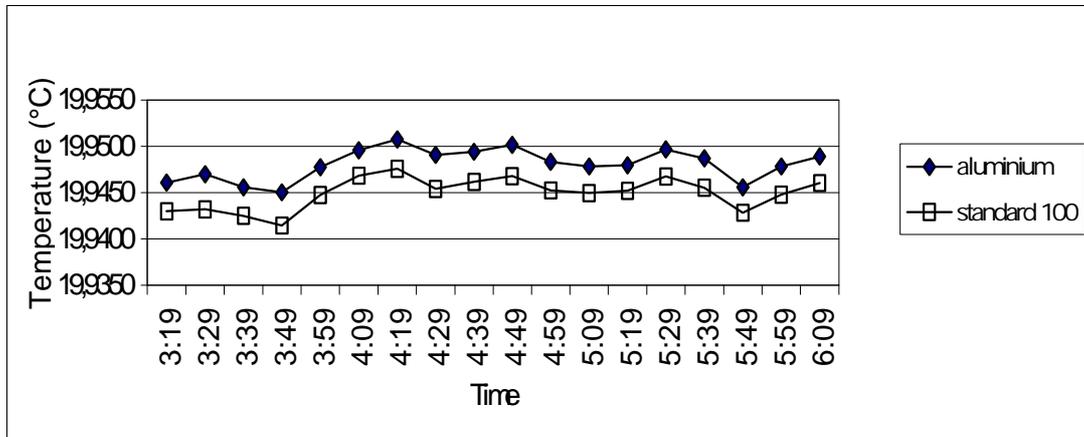

Figure 1. Temperature comparison between the aluminium base plate and the gauge block

3.3 Material of the comparator table

Some simulations with different materials have shown the importance of the material and the colour of the table. The existing tables (tested on Mahr and Cary comparators) do not have ideal properties because of dark colours. The temperature is constantly above the air temperature. When gauge block is put on the table, the temperature starts to grow and the length of the gauge block is changing. Typical temperature behaviour after putting gauge block on the table is shown in figure 2. In this case gauge block was put on the comparator table at 10:41 and at 10:50 calibration of this gauge block was finished. From this case we can learn, that the gauge block should not be measured immediately after putting it on the table. It should be stabilised for approximately three minutes. Probe 1 in Figure 2 was measuring the reference gauge block temperature and probe 2 was measuring the temperature of measured gauge block. We can see that the temperatures of both gauge blocks after stabilisation are not equal.
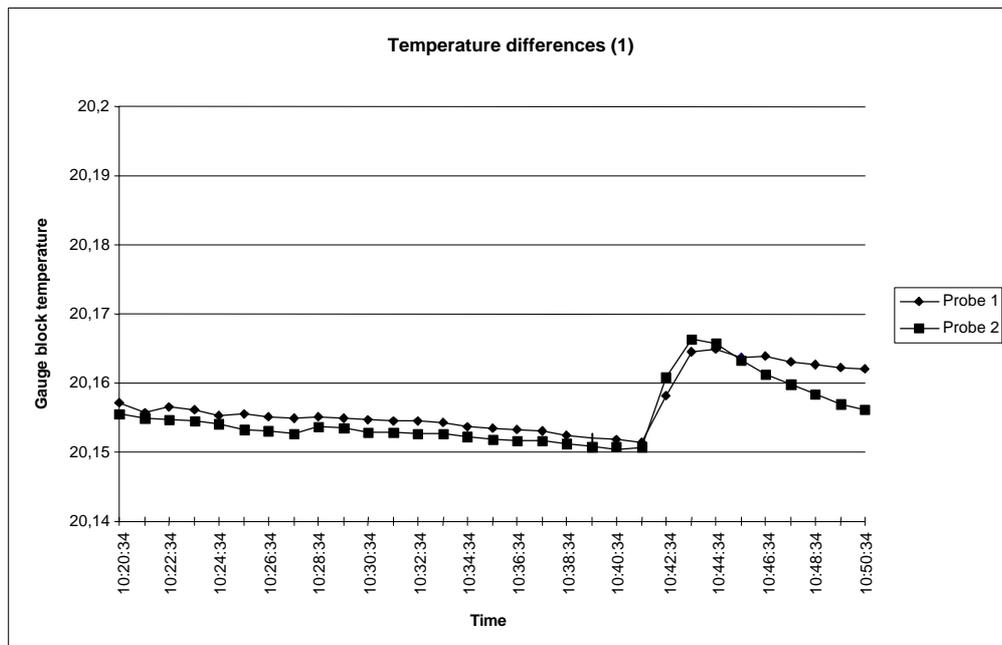

Figure 2. Thermal behaviour of gauge blocks after putting them on the comparator table

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3.4   Thermal expansion coefficient of the gauge blocks

Thermal expansion coefficient must be determined with standard uncertainty $u \leq 0{,}3 \cdot 10^{-6} {}^{\circ}C^{-1}$. For this we shall determine thermal expansion coefficient within the limits of $\pm 0{,}5 \cdot 10^{-6} {}^{\circ}C^{-1}$ Usually this is not a problem, but sometimes we get gauge blocks without any data about α. In such cases we can not be sure that α was determined with proper accuracy. Temperature deviations must therefore be diminished to minimum possible values.

Another problem is the difference between thermal expansion coefficients of the reference and measured gauge blocks. Uncertainty contribution of his difference in μm is expressed by the equation:

$$u = u(\Delta\alpha) \cdot l_e \cdot \theta \quad (1)$$

where: u - uncertainty contribution in μm
$u(\Delta\alpha)$ - uncertainty of the difference of thermal expansion coefficients (in ${}^{\circ}C^{-1}$)
$\cdot l_e$ - nominal length of gauge blocks
θ - maximum possible temperature deviation

If uncertainty of the difference between thermal expansion coefficients is $0{,}6 \cdot 10^{-6} {}^{\circ}C^{-1}$, and maximum possible temperature deviation is $0{,}1{}^{\circ}C$, than the uncertainty contribution in calibration of 100 mm gauge block is $0{,}006\ \mu m$ what is the maximum possible limit for our demands. If temperature deviation is $0{,}3{}^{\circ}C$, we get the value of $0{,}018\ \mu m$, what is far too much.

From the above example we can conclude that temperature deviations and the limits of determination of thermal expansion coefficient must be within very low values. These two components are in strong correlation and influence the length dependent part of the combined uncertainty.

3.5   Indentation of different gauge blocks by the applied measuring force

Research in this field is made in order to be able to calibrate gauge blocks of different materials. The indentation is calculated by the following (Roark's) equation:

$$i = 1{,}4 \cdot \sqrt[3]{\frac{F^2 \cdot C_E{}^2}{d}} \qquad (2)$$

$$C_E = \frac{1 - \nu_1{}^2}{E_1} + \frac{1 - \nu_2{}^2}{E_2} \qquad (3)$$

where: i - indentation
F - probing force
d - probing ball diameter
ν_1 - Poisson number of the probing ball material
ν_2 - Poisson number of the gauge block material
E_1 - elasticity module of the probing ball material
E_2 - elasticity module of the gauge block material

If probing force is $0{,}1$ N, probing ball of $d = 2$ mm is made of hart metal and gauge block is made of steel, than the indentation is $0{,}116\ \mu m$. For the gauge block made of hart metal this value would be $0{,}081\ \mu m$. The difference of the both indentations is $0{,}035\ \mu m$. The greatest problem in this calculations is to get right values for E and ν. Every deviation of these values causes uncertainty of indentation calculation. The second problem is evaluation of probing force, which shall be measured very precisely. Therefore, some experimental work has already been performed in order to evaluate uncertainty of indentation. It was found out that the standard uncertainty can be held in the limits of $0{,}008\ \mu m$.

3.6   Calibration of the comparator

Uncertainty contribution can be diminished by more accurate calibration of gauge blocks. No research was performed in this direction, since it is hard to do anything significant in this field in the laboratory.

3.7   Automation of the measurement process

In order to eliminate human influences, the calibration process will be automated. A new Cary

comparator with movable table has been purchased for this purpose. The manipulator for loading gauge blocks will be controlled with pneumatic mechanism. Control units and mechanics is already being designed in our laboratory. The controlling and calculating software will also be designed by the laboratory staff. Some algorithms based on metrological knowledge, experiences and research have already been made.

The system is designed in such way that series of ten gauge blocks will be measured in one step (not the whole set of gauge blocks). Such design will require less space in measuring room. All control units will be located apart from the comparator or even outside the measuring room, only executing pneumatic elements will be mounted on the measuring device. The comparator will also be isolated with special box in order to eliminate air flow around gauge block during the measurement.

The project of automation of gauge block calibration is included in the national research programme for the next two years. Beside better calibration results it is expected that the work will be more efficient. The measurement process will be faster and some repetitions of bad measurements caused by human factor will not be necessary any more.

4   CONCLUSIONS

Critical uncertainty contributions were extracted from the uncertainty budget and analysed in order to define actions for their optimisation. It was found out that heating of gauge blocks by radiation of the operator and illumination bodies causes most troubles and must therefore be eliminated from the process. This will be done by automating the process and by choosing proper materials. the only critical component that can not be influenced much is calibration of a gauge block comparator.

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