REDUCTION OF THERMAL EFFECTS ON PRECISE DIMENSIONAL MEASUREMENTS

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ABSTRACT

Inhomogeneous temperature fields are a source of error in precision dimensional measurements. To reduce these dimensional measurement errors, among other approaches, the complex measurement instrumentation can be thermally stabilized or cooled. At the example of the Measuring Microscope of the Nanometer Comparator at Physikalisch Technische Bundesanstalt, active and passive cooling strategies are shown and advantages and drawbacks of the approaches are discussed. Concluding from those general ideas, a new passive thermal cooling approach which uses the latent heat of the melting process of a Gallium-Tin eutectic alloy is presented for thermal stabilisation of the measuring instrumentation. The design and development of the cooling element are explained and validating measurements which demonstrate a thermal stable time span of 6 h are shown.

Index Terms - Thermal optimisation, Thermally induced errors, Phase change material, PCM,

1. INTRODUCTION

Some of the critical factors limiting the precision of dimensional measurements are insufficient temperature stabilisation, significant temperature gradients or heat introduction in precision engineering and measurement instrumentation or machine tools [1-3]. In the EURAMET Joint Research Project "Thermal design and time-dependent dimensional drift behavior of sensors, materials and structures" [4] researchers from European national metrological institutes and research institutes are working together on improvements in this research field, but mainly focused on precision dimensional measurement instrumentation.
Thermal improvement or thermal optimization of the instrumentation aims the reduction of the instrumentations sensitivity to heat load or temperature changes. The tools which can be used to achieve this are manifold. They span from

a. Constructive changes in the instrumentations design,
b. Cooling of the instrumentation or heat sources to
c. Mathematical or physical compensation techniques.

The design of precision dimensional measurement instrumentation is mostly developed to achieve the best resolution and uncertainty of dimensional measurements. Here, the measurement principle, the used components and boundary conditions are fixed, wherefore thermal optimization by significantly changing the design or materials (a) of relevant components are often impossible. Compensation techniques (c) require thermal models which precisely describe the dependency of the observed variable (length) to the disturbing quantity (temperature, heating power). The more complex the instrumentation is and the more varying the measurement conditions are, the more difficult model estimation becomes.

This article is focused on the investigation and comparison of cooling techniques for precision dimensional measuring instrumentation (b). This investigation is carried out at the example of the Nanometer Comparator of the Physikalisch Technische Bundesanstalt in Braunschweig (Fig. 1). This piece of equipment is used for precision dimensional measurements of incremental length measurement systems (e.g. linear encoders, line scales) with nanometer uncertainty. Although the measurement principle is interferometric, a microscope with a UV camera is used to observe the stripes of the scales (Fig. 2).

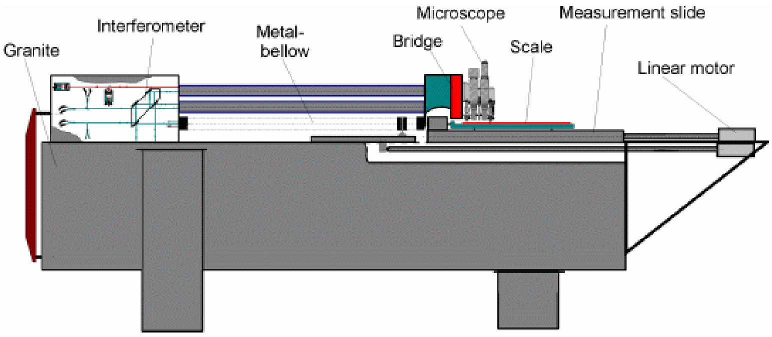

Fig. 1 - Schematic view of Nanometer Comparator

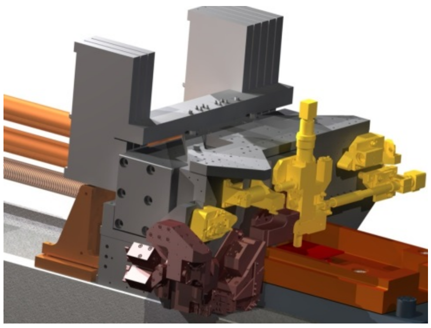

Fig. 2 - Detailed view of measuring microscope (yellow)

For the measuring microscope, thermal images of the set-up were made and the UV-camera was identified as a significant heat source (Fig. 3). Its temperature raises during a measurement approximately by 18 K above the ambient temperature of 20 °C, which could cause dilatations in the mechanical set-up.

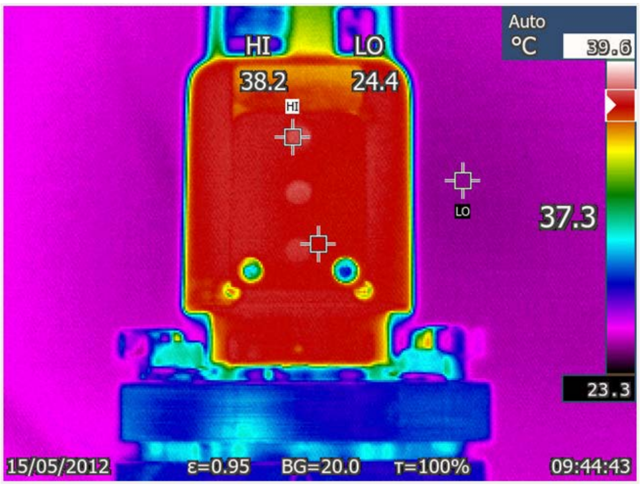

Fig. 3 - Thermal image of microscope camera mounted at a holder

To improve this situation and to reduce the thermal effects on a measurement, a suiting cooling approach and design had to be chosen, which provides stable thermal conditions during a dimensional measurement, realises a thermal decoupling of the camera from the measuring instrumentation and provides a thermal shield between the warm camera and the comparator set-up.

2. THERMAL DESIGN OF PRECISION INSTRUMENTS AND COOLING STRATEGIES

In general, precision measuring and precision manufacturing instrumentation should be designed in compliance with some well-known design rules:

- Heat sources like drives or electronic devices should be placed far away from thermally sensitive parts or the object of investigation
- Thermally low conducting materials should be used to reduce heat flow into thermally sensitive parts (high temperature gradients occur)
- Thermally high conducting materials should be used to guide heat to heat sinks or thermally insensitive components
- Materials with low coefficients of thermal expansion (CTE) should be used where high temperature gradients occur
- CTE of materials of joint components should be suited
- The mechanical design should be symmetric to heat sources to get symmetric dimensional deformations rather than tilting or torsion
- …

In many cases not all design rules can be respected in a design and significant influences from temperature and temperature gradients on the instruments remain. In these cases typically additional cooling is used to improve the situation. Here, one can distinguish between active and passive cooling.

2.1 Active cooling

In active cooling approaches actively controlled heat sources or heat sinks are used to control or stabilise the temperature of a component or instrumentation. Typical sources or sinks which are utilised are peltier elements, electrical heaters, stirling motors or heat pumps. Typically, they are applied in combination with heat exchangers to temper working media like gases or fluids, which exchange the heat with the components to be stabilized. In some cases the active sink can be coupled directly without using working media to the component.

Active cooling approaches offer certain advantages. The temperature at the position of interest can be controlled directly, different types of sinks with different power are available and the power of the exchanged heat can be adjusted. But, applied to precision dimensional measurement instrumentation they also have drawbacks. Most of the types of sources contain moving or rotating parts which can cause mechanical vibrations in the measurement instrumentation. These vibrations can cause dimensional measurement errors, especially when uncertainties at the nanometer level are targeted. The moving working fluids in pipes or even ventilating air can be a source of disturbing vibrations either. The application of active cooling approaches requires knowledge in controller design, models of the controlled system and certain equipment.

2.2 Passive cooling

Constructive changes in the instruments which are made to optimise the paths of heat flow or to minimise the thermal sensitivity of the set-up one can summarise under passive cooling. Here, by means of constructive changes the parasitic heat is guided away to thermally insensitive components or to the environment. The thermal optimisation is realised without active controlling or influencing of heat sources.

The starting point of a thermal optimisation is a sufficient understanding of the heat transport phenomena or temperature fields in the instrumentation. They can be acquired by means of temperature measurements or by thermal modeling and simulation of the instrumentation.

The advantages of passive cooling approaches are a reduced effort compared to active cooling approaches, no electronics, controllers and sensors are needed and no mechanical vibrations occur. Disadvantageous are a usually minor cooling power compared to active approaches, resulting temperatures which are depending on the boundary conditions and temperature deviations which will not equal to 0 K.

3. PASSIVE COOLING BY MEANS OF LATENT HEAT

To avoid any mechanical vibrations, it was decided to use a passive cooling approach to cool down the camera of the measuring microscope. This camera has an installed electrical power of $P \approx 4.5$ W, which is mostly transformed to parasitic heat during operation. The Nanometer Comparator and measuring microscope are used in a temperature stabilised chamber at $T_{amb} = 20$ ºC. In this chamber a continuous airflow happens from the ceiling to the bottom with $v_{air} = 0.2…0.4$ m/s. This air flow can be used to cool down the microscope and camera. Nevertheless the camera heats up significantly, what can be seen in the coloured temperature field that was estimated by means of a numerical calculation (Fig. 4).

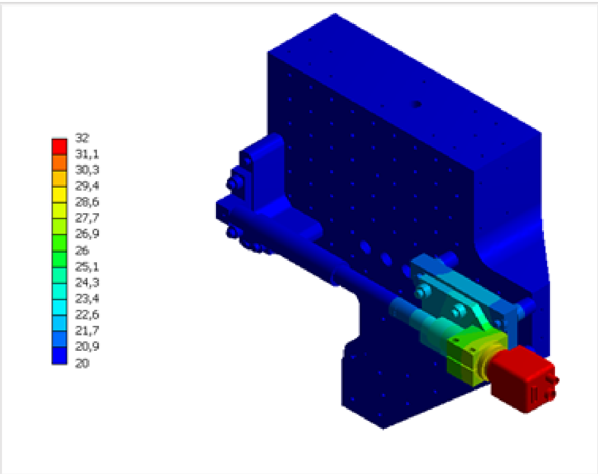

Fig. 4 - Simulated temperature field of the measuring microscope and mounted camera (red)

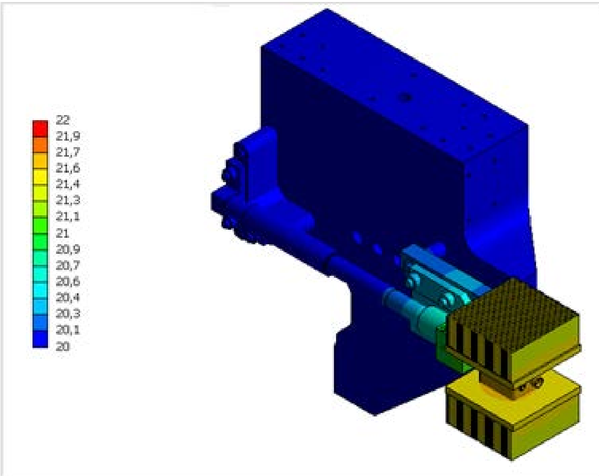

Fig. 5 - Simulated temperature field of the mounted camera with cooling elements

This temperature increase could be reduced by realizing a better thermal coupling between camera and air for instance by mounting cooling elements to the camera (Fig. 5). But even here, a significant temperature difference to T_{amb} and temperature gradients in the camera mounting remain due to the finite thermal conductivity of the cooling element and the low convection coefficient of $\alpha \approx 8..12$ $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ at air flow conditions. A further optimisation of the camera mounting and the cooling elements could bring additional minor improvements, but the camera would remain a hot spot which exchanges heat with the microscope and comparator via conduction, convection and radiation.
That's why a new passive cooling approach was developed. It uses a specific Phase Change Material (PCM) which surrounds the camera and acts as a heat sink. During the operation of the camera, most of the parasitic heat is guided into this material and is stored as latent heat of the melting process. During this melting, the PCM remains at a constant temperature $T_{m.}$ As a consequence of this, the camera and especially its mounting do not heat up that much.
Most PCMs which are used for energy storage purposes are based on hydrocarbons or salt hydrates which have a broad temperature range of some Kelvin for melting. This property is unsuitable for application in a cooling element. Here, a nearly constant temperature during the phase transition is needed to achieve a suiting thermal stabilisation of the camera. That's why a eutectic Ga-Sn8%(at)-alloy was chosen as PCM instead [5, 6]. It changes its phase narrowly at $T_m = 20.5$ ºC. Moreover, T_m is close to room temperature which makes a thermal stabilisation close to the working temperature of the Nanometer Comparator possible.

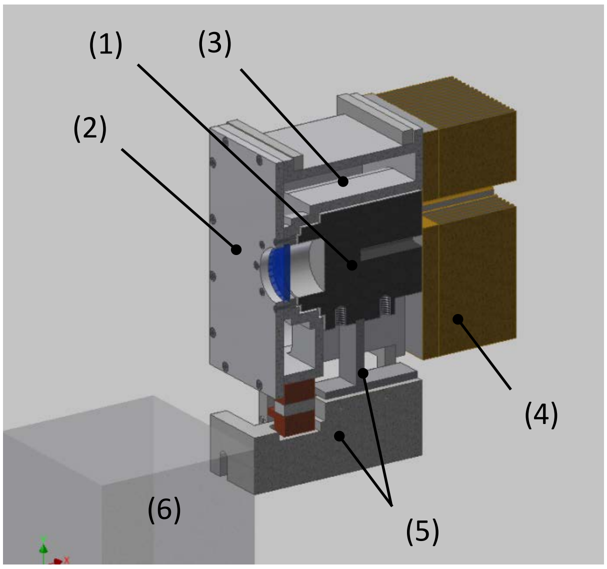

Fig. 6 – Drawing of demonstration model in sectional view

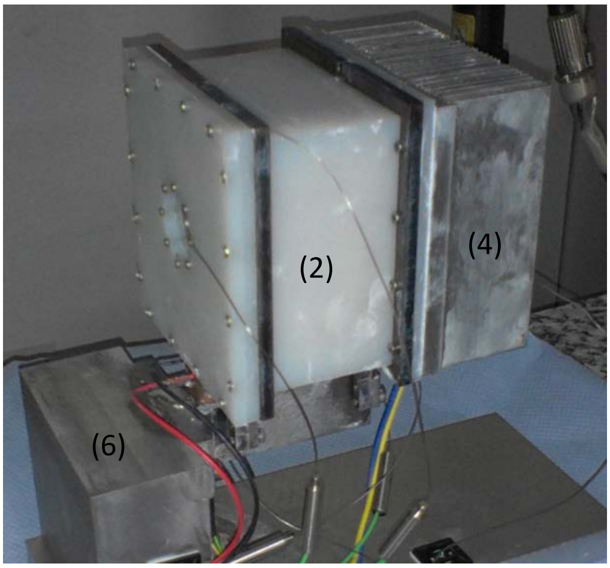

Fig. 7 – Demonstration model with temperature sensors in climatic chamber

For proof of principle, a demonstration model of this PCM-cooling element was developed and optimised using thermal Finite Element Calculations. The design of the demonstration model can be seen in Fig. 6 and in Fig. 7. In this design the camera (1) is surrounded by a polyethylene vessel (2) with a cavity (3) in which the PCM is filled in. The camera is completely surrounded by the PCM and its container except at the camera's bottom side and the backside. At the bottom side the mounting elements (5) join the camera and the base plate (6). At the backside the camera is attached to a heat sink which provides an additional cooling.

The functional principle of the PCM cooling element can be understood best by discussing the results of a transient thermal simulation of a typical measurement run (Fig. 8). In this simulation the whole demonstration model is at thermal equilibrium at $T_{amb} = 20$ °C in the beginning. At $t = 0$ h the camera is switched on and starts to heat up. After 0.5 h camera and heat sink reach a temperature level of 22 °C to 23 °C which is kept for next couple of hours.

The exterior of the PCM-container, the mounting elements and the base plate remain at ambient temperature. During this time span the parasitic heat of the camera is absorbed by the

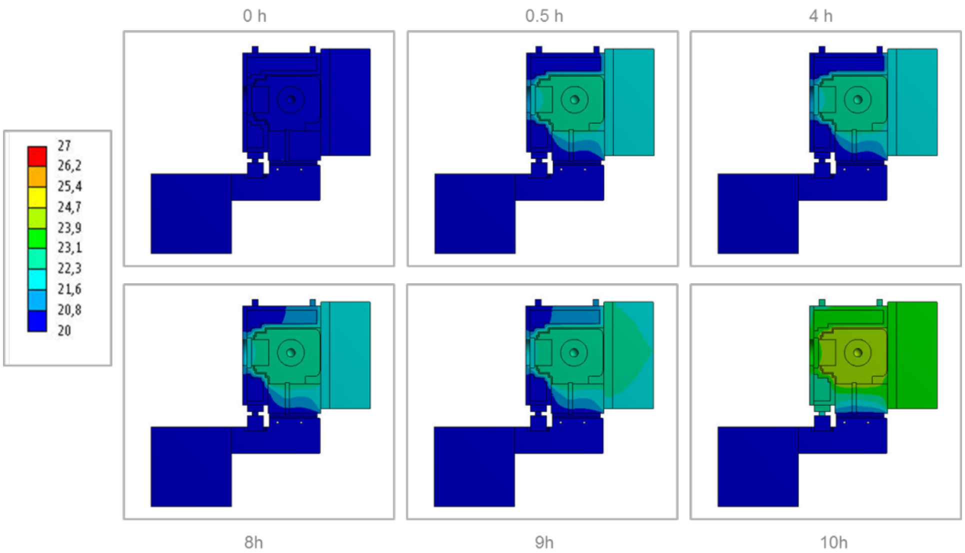

Fig. 8 – Simulated temperature field inside the demonstration model while a typical measurement with the measuring microscope is performed

PCM and the camera is additionally cooled by means of the heat sink. After 4 hours, the temperature field hasn't changed significantly. The cooling and the thermal stabilisation are still active. When the elapsed time gets closer to 8 hours one can observe, that the temperature of the PCM slowly starts to increase (light blue areas in Fig. 8). In those areas the PCM is already molten and the thermal shielding starts to break. After 10 hours all of the PCM is molten and the temperature of the demonstration model has increased significantly.
The same behavior can be observed in a measurement in a climatic chamber which is at similar conditions as where assumed for the thermal simulations (Fig. 7, Fig. 9). In this measurement the temperatures in the demonstration model stabilise after 0.5 to 1 hour after switching on the camera and reach a plateau phase which is typical for melting procedures. For the next 6 hours, the temperatures in the demonstrator increase only slightly and the temperature at the mounting T_{mount} remains constant within a span of 0.1 K. This evidences, that the temperature at the mounting and the exterior walls of the PCM-container remain stable and the passive thermal cooling by means latent heat is performing well. After 7 hours, the temperatures increase significantly since most of the PCM is already molten. With that, the thermal stabilisation diminishes and the material must be solidified again before the next measurement run.

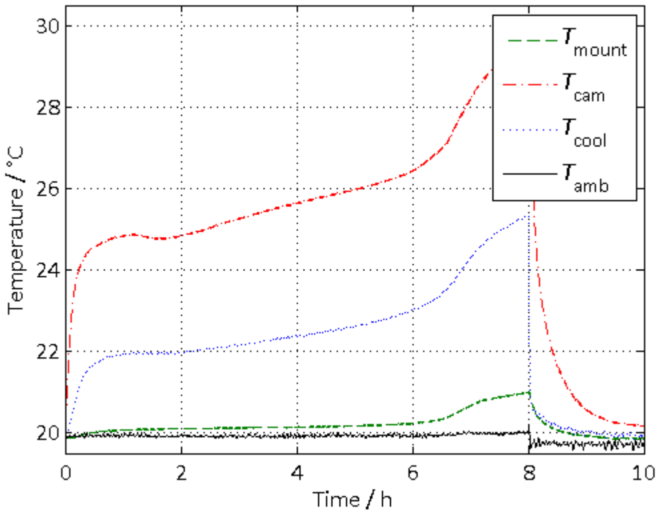

Fig. 9 – Measured temperatures at the demonstration model

4. SUMMARY

When active cooling methods are used mechanical vibrations can occur, which can disturb precision dimensional measurements. Hence, a new passive cooling approach was used for cooling of the camera of the Nanometer Comparator's Measuring Microscope. In this approach, a eutectic alloy of gallium and tin with a melting temperature of $T_m = 20.5$ ºC is used to thermally stabilise the measurement instrumentation and to shield the warmer camera. By means of a demonstration model it was shown, that the temperature at the camera mounting and at the exterior of the shield remained constant within 0.1K within a period of about 6 hours. This time span of sufficient thermal stability could be used to perform dimensional measurements at the Nanometer Comparator.

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