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Thermal decoupling of heat sources by means of PCM-shielding

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Abstract:

For optimisation of the thermal conditions in measuring instrumentation, one can use different active (air, liquid, peltier cooling) and passive cooling approaches. Since active cooling approaches may retroact to the measurement instrumentation or may add mechanical vibrations to the measuring instrumentation, passive cooling often is applied in instrumentation of highest measurement precision. Since the cooling power of passive cooling approaches is limited, a new passive cooling strategy was developed at Technische Universität Ilmenau, which can be applied for thermal shielding or cooling of heat sources. This new passive cooling approach uses a specific Phase Change Material (PCM) with a melting temperature of $T_\mathrm{m} \approx 20.5$ °C as a heat sink. During the operation of the heat source, most of the parasitic heat is guided into this material and is stored as latent heat of the phase transition. As a consequence of this, the heat source is thermally shielded and the temperature in the surrounding components is stabilised. This cooling principle was validated at the example of a camera which is part of the measuring microscope of the Nanometer Comparator at Physikalisch Technische Bundesanstalt, PTB, in Braunschweig. For proof of principle of PCM-shielding, a demonstration model of a PCM-cooling element was developed and optimised for this camera using thermal Finite Element Calculations.

Key words: PCM-shielding, Phase-Change-Material (PCM), thermal optimisation, passive cooling, Finite-Element–Modeling (FEM)

Introduction

Critical factors which limit the precision of dimensional measurements are insufficient temperature stabilisation, significant temperature gradients or heat introduction in precision engineering and measurement instrumentation. Due to these thermal influences, dimensional changes of the mechanical set-up may arise as well as temperature changes of the measuring objects or time-dependent thermal effects.

A typical example for such measurement instrumentation is the Nanometer Comparator at Physikalisch Technische Bundesanstalt in Braunschweig, Germany (Fig. 1) [1]. It is used for precision dimensional measurements of incremental length measurement systems (linear encoders, line scales) with nanometer uncertainty. Although the measurement principle is interferometric, a microscope with UV-camera is used to observe the stripes of the scales. Due to joules heating, this camera heats up when it is switched on and its temperature raises significantly above the ambient temperature of 20 °C during a measurement (Fig. 2). This temperature change may lead to variations in the local temperature field close to the measuring microscope and the comparator scale. Due to that, time dependent dilatations in the set-up may occur which will lead to deviations in the dimensional measurement.

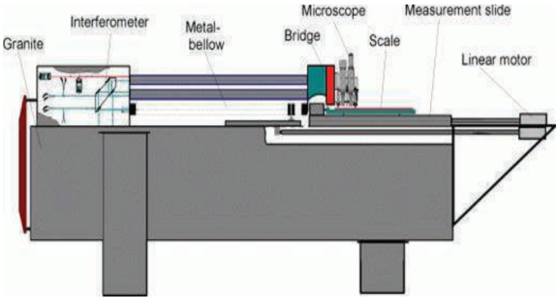


Fig. 1 Sketch of the Nanometer Comparator

Since the parasitic heat which is generated by the camera of the measuring microscope may not be reduced directly, one must apply additional cooling to the instrumentation [2, 3]. Here the approaches may be distinguished between active and passive cooling methods.

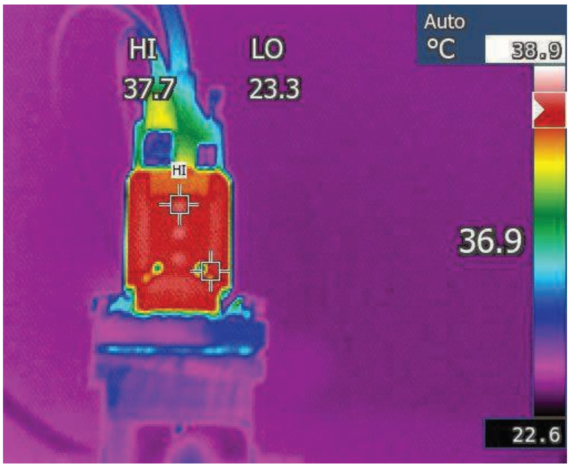


Fig. 2 Thermal image of UV-camera.

In active cooling approaches servo-controlled heat sources or heat sinks are implemented to a component or instrumentation. They are used to improve the thermal situation, to reduce or stabilise temperatures or to level temperature gradients. The type of the used sources or sinks depends on the application and ranges from electrical heaters and peltier elements to stirling motors or heat pumps. Sometimes the sources or sinks are coupled directly to the components to be tempered. But mostly they are used in combination with heat exchangers and working media like gases or fluids, which transport the heat.

Active cooling approaches offer certain advantages. They can provide a high cooling power due the good thermal coupling resulting from forced convection, high flow rates or low temperatures of the working fluid. The resulting temperature fields can be servo-controlled to be quasi-static or less time varying. Different types of heat sinks and methods are available, whereby a customized adaption to the specific cooling problem is possible. But, applied to precision dimensional measurement instrumentation they also have a drawback. Due to the circulating fluids and moving parts, the cooling set-ups often may cause mechanical vibrations. These vibrations can influence mechanical sensitive equipment and may disturb measurements, which is disturbing in particular when measurement uncertainties at the nanometer level are targeted.

No mechanical vibrations occur when passive cooling approaches are used. In these approaches, the construction, geometry or materials of the set-up are changed aiming to improve the heat flow and the thermal coupling. Parasitic heat is guided to thermally insensitive areas or the environment without active control of heat sources. The effort for the implementation of passive cooling is mostly less than for active cooling, since no electronics, controllers or electrical components are needed. Adverse properties of passive cooling approaches are a typically minor cooling power, temperature fields which are depending on environmental conditions and remaining temperature deviations which may not be controlled to zero.

Preliminary considerations on passive cooling of the camera

The thermal optimisation of the measuring microscope and the camera aims to meet three objectives:

I. minimise the heat flow into the instrumentation and to decouple the camera from sensitive parts

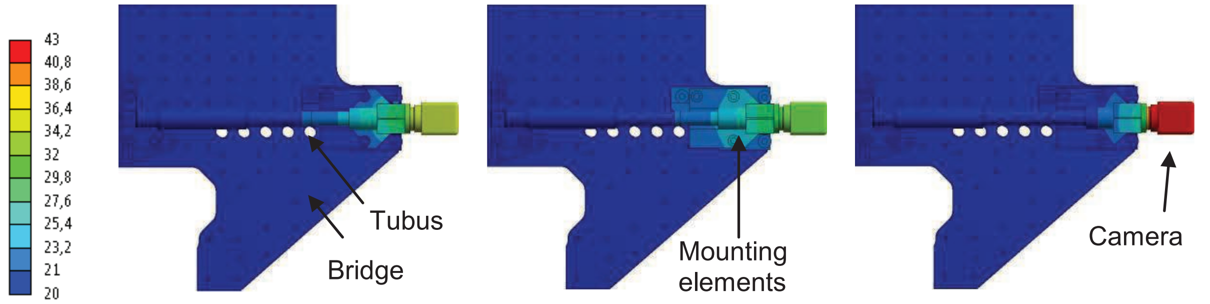
II. reduce the temperature of the camera

III. homogenise the temperature field in the measuring microscope

To achieve this, a sufficient understanding of the heat transport phenomena or temperature fields in the instrumentation must be acquired, which was done by means of temperature measurements (Fig. 2) and by thermal modelling and simulation of the instrumentation (Fig. 3).

Heat sources which are mounted on sensitive instrumentation can be decoupled by using thermally low conducting materials (thermal conductivity $\lambda \to 0$) for mounting elements. Here, Zerodur (λ(20 °C) ≈ 1.5 W·(m·K)-1) or Invar (λ(20 °C) ≈ 10.5 W·(m·K)-1) can be a better choice than steel (λ(20 °C) ≈ 15..30 W·(m·K)-1) or aluminium (λ(20 °C) ≈ 235 W·(m·K)-1). Furthermore, the materials should have a low (zero) coefficient of thermal expansion (CTE) to minimise dilations in the set-up due to residual temperature gradients, which is given for Invar and Zerodur.

For the measuring microscope the mounting situation was investigated by means of FEM-calculations, in which the following boundary conditions were assumed: The camera has an installed electrical power of P ≈ 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 °C. In this chamber air continuously flows from the ceiling to the bottom with v_{air} = 0.2 – 0.4 m/s. which cools down the microscope and camera.



Scale in °C | Camera mounting steel/ Invar | Camera mounting Zerodur/ Invar | Mounting and tubus Zerodur/ Invar

Fig. 3 Thermal simulations of the measuring microscope and a mounted camera (heat source). Manufacturing the mounting elements and the tubus from Zerodur (right picture) increases the temperature of the camera (red), but reduces the temperature gradients in the tubus and bridge (blue) compared to a mounting of steel (left picture). By using Zerodur, a thermal decoupling is achieved.

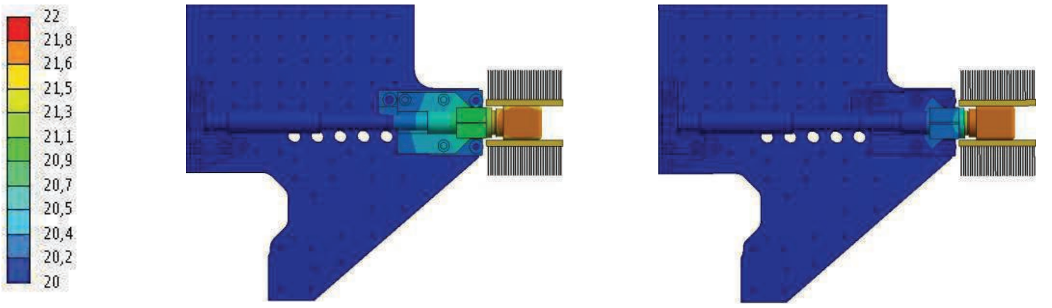
In the simulations it was found, that criterion I and criterion III could be fulfilled best when relevant parts of the mounting elements would be manufactured from Invar and Zerodur. Doing this, the heat flow from camera into the measuring microscope can be reduced and the temperature of the microscope and bridge can be kept close to 20 °C (Fig. 3, right). The drawback of this approach is, that the camera itself heats up stronger (≈ 43 °C) than if it is coupled by Invar and steel (≈ 35 °C, Fig. 3, left).

Changing the materials and the mounting situation does not improve the thermal situation at all, since the thermal coupling between heat source and cooling medium (air) is too weak and the thermal heat transport resistance R_α between camera surface and air is too high. Neglecting the radiation heat exchange between ambient and camera, R_α can be estimated from (1).

$$R_\alpha = \frac{1}{\alpha_{air} A_{cam}} \qquad (1)$$

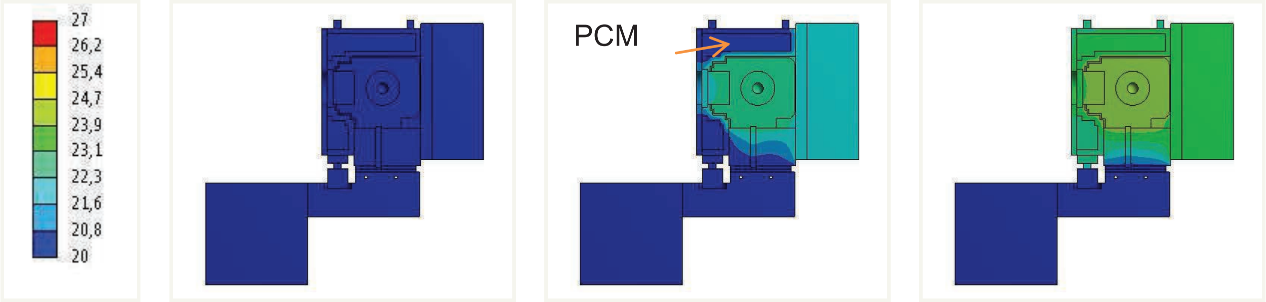
Here α_{air} is the mean convection coefficient and A_{cam} the camera surface. Since the convection coefficient is quite predetermined due to the fixed air velocity in the temperature stabilised chamber, a reduction of R_α could be reached only by increasing the surface where the heat exchange takes place. This can be done by mounting additional heat sinks to the camera. The effect of the heat sinks can be seen in Fig. 4, where aluminium heat sinks with an increased surface of $55 \cdot A_{cam}$ were used. Due to the better thermal contact to the environment, the temperature of the camera gets decreased to approximately 21.8 °C, which is a remarkable improvement.

At this point, a further significant reduction of the temperature may not be achieved just by adding heat sinks or changing the mounting situation. An elevated temperature of the camera and temperature gradients in the microscope remain due to the internal resistances to thermal conduction and heat exchange between camera and the microscope and bridge still takes place (by radiation and thermal conduction).



Scale in °C | Camera mounting steel/ Invar | Mounting and tubus Zerodur/ Invar

Fig. 4 Thermal simulations of camera with attached fin coolers



Scale in °C

Camera switched off

Camera switched on – PCM is melting – temperature is stable

Camera switched on – PCM is molten – temperature increases further

Fig. 5 Thermal simulations of a mounted camera (heat source) which is stabilised in temperature by means of a Phasen Change Material (PCM).

Shielding by means of a Phase Change Material (PCM)

To achieve a further decoupling of the camera from the set-up, a new passive cooling approach was developed, in which the classical approach was enhanced by including a phase change material (PCM) to the cooling setup. Here, the heat source (camera) is encased by a PCM. This PCM absorbs the parasitic heat while it is melting. During the melting process, the temperature of the PCM remains at the material specific melting temperature T_m. Due to this thermal damping effect the PCM thermally stabilises the temperature field in the measuring microscope and camera and shields thermally sensitive surrounding parts from the camera's heat. In this approach, the PCM's latent heat of melting is used as a heat sink.

Depending on their individual thermophysical properties, PCM's are utilized in thermal energy storages, like in solar power plants, or for thermal stabilisations e.g. of buildings. Widely used materials are hydrocarbons, waxes or salt hydrates. For cooling the camera, a PCM must be chosen which has a melting temperature T_m close to and slightly above 20 °C. Some of the waxes and hydrocarbons fulfill this criterion, but they typically have a broad temperature range of some Kelvin in which the melting takes places. This is unsuitable for cooling the camera, since it would result in a thermal drift of the camera's temperature during the melting procedure.

That is why a eutectic alloy of Ga-Sn(18% wt.) was chosen as PCM. Eutectic alloys or pure materials typically do melt in a temperature interval of some Millikelvin to some ten Millikelvin wherefore they are preferred to use. Furthermore the Ga-Sn alloy has a melting temperature of 20.5 °C which is suiting for the passive cooling application [4,5].

For testing the principle of PCM-shielding, a demonstration model was constructed and built up (Fig. 6). The camera which is located in the center of this model, is surrounded by a plastic container in which the alloy is filled in. At the camera's back side is a fin cooler which additionally cools down the camera. The camera itself is fixated with Zerodur and Invar mounting elements. The whole assembly may be surrounded by a thermal isolation.

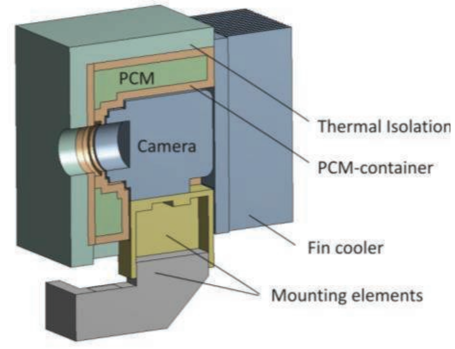


Fig. 6 Schematic sketch of demonstration model with camera and PCM-container

The design was validated an optimised by means of thermal calculations again. Their results and working principle of the PCM-shielding can be seen in Fig. 5. When the heat source is switched off, the temperature inside of the demonstration model is homogeneous (left picture). The temperature increases when the heat source (camera) is switched on, but it is stabilised at the melting temperature of the PCM due to the phase change (middle picture, blue areas). The whole PCM is molten approximately 8 hours after switching on the camera. Then the phase change is completed, the stabilisation is finished and the temperature in the demonstration model rises further (right picture).

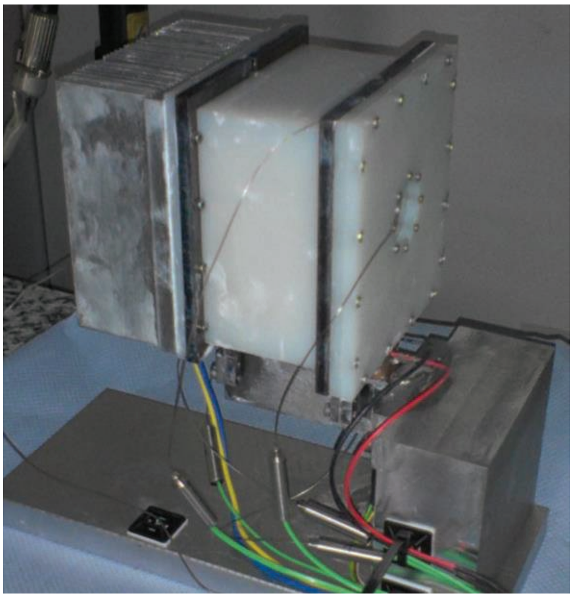


Fig. 7 Demonstration model in climatic chamber; temperature monitoring points are marked by colored dots

The demonstration model was also tested in a climatic chamber at 20 °C (Fig. 7), where it was mounted on a base plate. Several temperature sensors (thermocouples of type K) where distributed in the set-up. In the measured temperature curves (Fig. 8), a quite similar behaviour of the PCM-shielding and the prediction in the simulations can be seen. After switching on the camera at $t = 0$ h, the temperature in the camera and at the fin cooler increases. Due to the starting phase transition, the temperatures get stabilised after approximately one hour. The temperature at the mounting elements remains at 20.1 ± 0.05 °C until the solid-liquid phase boundary starts to break at 6 h. Within this time span, the thermal shielding is active. After approximately 7 h most of the PCM is molten and the temperatures start to increase. At this time, the thermal stabilisation is finished and the material needs to be solidified again for another use.

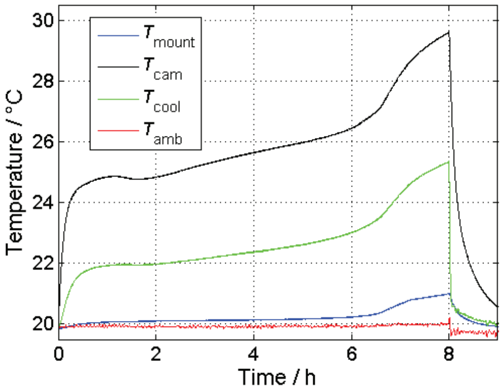


Fig. 8 Measured temperature curves after the camera was switched on a t = 0 h.

Conclusion

A new passive cooling approach was developed and validated which enables a thermal shielding and cooling heat sources. The method was tested exemplarily for the camera (heat source) of a measuring microscope. The method uses the latent heat of melting of a eutectic alloy of Ga-Sn(18% wt.) as a heat sink which allows a thermal stabilisation of camera and microscope close to the alloy's melting temperature $T_m = 20.5$ °C.

By means of thermal simulations and measurements on a demonstration set-up it could be shown, that the temperature at the camera's mounting elements was stable within ± 0.05 K in a time span of six hours. The temperature at the outside of the camera shielding could be decreased from approximately 36 °C to below 22 °C.

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References

[1] PTB, Working Group 5.21: Sketch of Nanometer Comparator at PTB. http://www.ptb.de/cms/en/fachabteilungen/abt5/fb-52/ag-521/messgeraete521.html

[2] Ruijl, T.A.M., Thermal effects in precision systems: Design considerations, modelling, compensation and validation techniques. *Diamond Light Source Proceedings*, 2011. 1(MEDSI-6): p. I.

[3] Mayr, J., et al., Thermal issues in machine tools. *Cirp Annals-Manufacturing Technology*, 2012. 61(2): p. 771-791.

[4] Burdakin, A., et al., Melting points of gallium and of binary eutectics with gallium realized in small cells. *Metrologia*, 2008. 45(1): p. 75.

[5] Heyer, D., B. Polomski, and S. Rudtsch. Untersuchung binärer eutektischer Legierungen für die Kalibrierung von Berührungsthermometern im Raumtemperaturbereich, *Temperatur 2013*, 2013, Physikalisch Technische Bundesanstalt.