INDUSTRIALLY APPLICABLE MINIATURE FIXED-POINT THERMOCOUPLES

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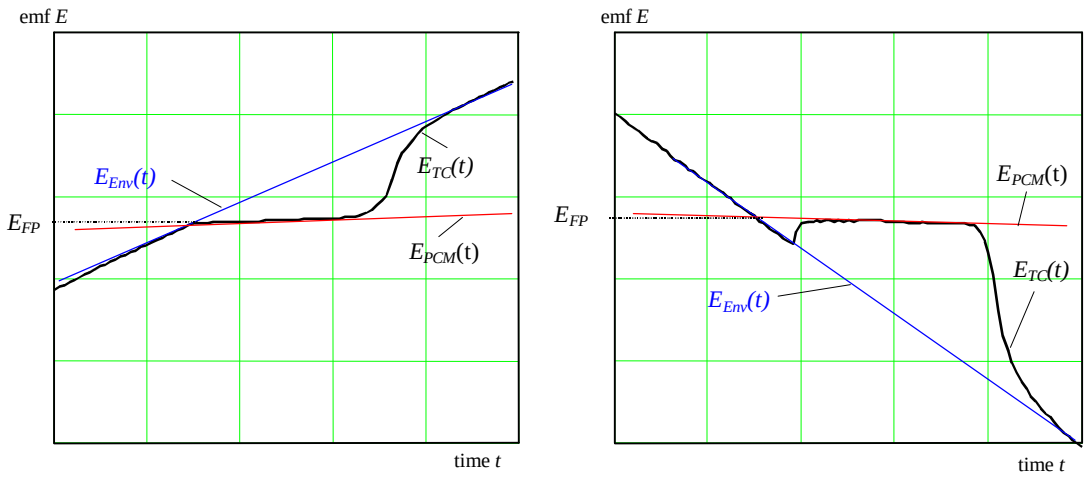
ABSTRACT

For the automated recalibration of important temperature measuring chains in power plants in a temperature range from 530 °C to 650 °C, thermocouples with integrated miniature fixed-point cells have been developed. Practical long-term tests were successfully run with 7 different high-purity metals and binary alloys presenting phase transformation temperatures in this temperature range. A heating element additionally integrated into the thermocouple permits to carry out a recalibration of the entire measuring chain which can be set off from outside, also at constant medium temperatures. In the practical application, a calibration uncertainty at the fixed-point temperature of about 0.2 K, and measuring uncertainties at the operating temperature of < 1 K are achieved.

1. INTRODUCTION

If a suitable fixed-point material, encapsulated in a miniature fixed-point cell, is integrated into a temperature sensor, e.g. a thermocouple, the thermocouple emf curve will typically vary with time, which is due to the phase transformation processes taking place in case of any changes around the melting or also solidification temperature T_{FP} of the fixed-point material. From those temporal variations of the thermocouple emf, it is then possible to derive a calibration value $E(T_{FP})$ for the thermocouple or also for the entire measuring chain at the fixed-point temperature (Figure 1).



$E_{TC}(t)$	thermocouple emf curve measured
$E_{Env}(t)$,$E_{PCM}(t)$	regression straight lines
E_{FP}	emf value $E(T_{FP})$ to be determined, is obtained by calculating the point of intersection of these straight lines

Figure 1: Basic behaviour of the thermocouple emf curve during melting and solidification

This principle was successfully implemented in standard thermometers, which thus permit to represent the ITS-90 above 100 °C at very little uncertainty and relatively modest device-engineering expenses [1].

However, in order to be able to utilize this principle for recalibrating thermocouples in industrial applications, such as in power plants, the following prerequisites must be fulfilled:

- long-term stability of the miniature fixed-point cells also in case of temperature cycles and temperatures far above the phase transformation temperature,
- availability of small, metrologically optimal fixed-point cells which permit to be integrated into commercial temperature sensors,
- availability of fixed-point materials presenting well reproducible phase transformation temperatures near the normal operating temperature of the thermocouple so as to guarantee a measuring uncertainty as low as possible after a single-point calibration.

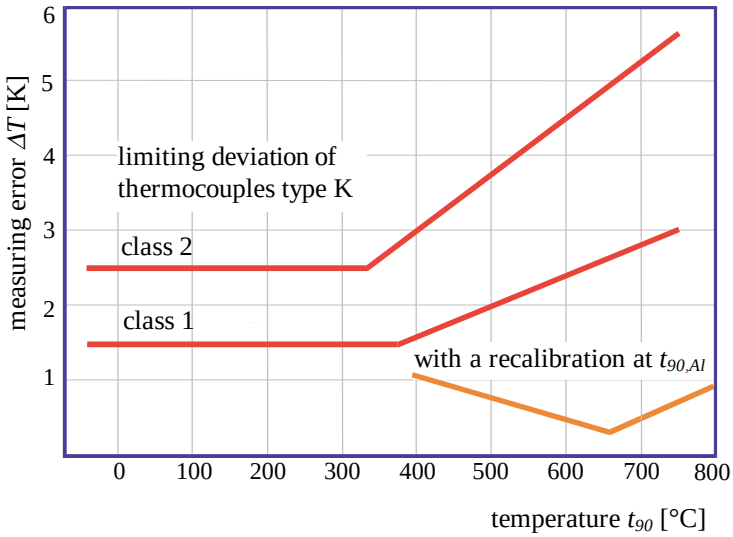


Figure 2: Admissible measuring errors of a thermocouple type K according to IEC 60571 and lower measuring uncertainty achievable with a recalibration at the aluminium fixed point

In fossil power plants, thermocouples of type K or N are normally applied in the superheated steam range where there are temperatures between 500 °C and 630 °C at present. Due to their admissible tolerances, the drift of their characteristics increasing with operating time, and the error limits of the subsequent elements of the measuring chain, the resulting uncertainties may amount to 5 K in normal cases. A recalibration in the test laboratory requires much effort and – as is known – does not reduce considerably the measuring uncertainty of the thermocouple.
However, this is a prerequisite which must be fulfilled in order to reduce distinctly the safety difference between the steam temperature and the maximum admissible temperature prevailing in the power plant, thus ensuring a higher degree of efficiency and a lower emission of toxic substances.

2. STRUCTURE OF MINIATURE FIXED-POINT THERMOCOUPLES FOR APPLICATION IN POWER PLANTS

In a first developmental phase of miniature fixed-point thermocouples of such kind, a sufficiently high long-term stability of aluminium and gold as fixed-point materials in ceramic miniature fixed-point cells towards considerable temperatures rises and marked temperature variations around the fixed-point temperature was achieved [2]. Furthermore, a number of essential factors, such as the design of the fixed-point cell, the constructional arrangement of the thermocouple and the component parts, and the material properties influencing the shape and evaluability of the calibration signals shown in Figure 1 have been investigated both by way of experiments and on the basis of model calculations [3, 4].

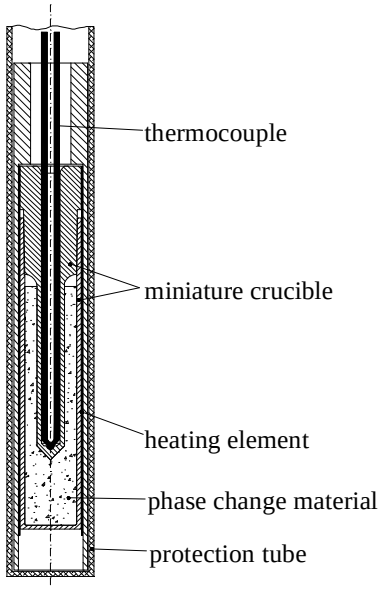


Figure 3: Structure of a sheathed thermocouple (outer diameter 6 mm) with miniature fixed-point cell and heating element

The results of FEM model calculations, which also took the phase transformation processes in the fixed-point material into account, permitted to develop a new design of miniature ceramic crucibles and to realize technologically the manufacture of the thin-walled component parts of high-purity ceramic (Al_2O_3, AlN), including the necessary filling and sealing technique. This helped to improve not only the mechanical and thermal properties of the crucible, but also the encapsulation of the fixed-point material, thus leading to a considerable increase in the long-term protection against any kind of impurities.

Because of the almost concentric arrangement of the thermocouple, the crucible walls, the fixed-point material and the metal sheath near the junction, and due to the optimized dimensions, geometry and arrangement of the single parts, it was possible to achieve a plateau behaviour of the thermocouple emf which could be evaluated much better, with the rates of change of the temperature being the same. This result was also due to the fact that the capacity of the cells was increased by about 50 %, with their outer dimensions being unchanged.

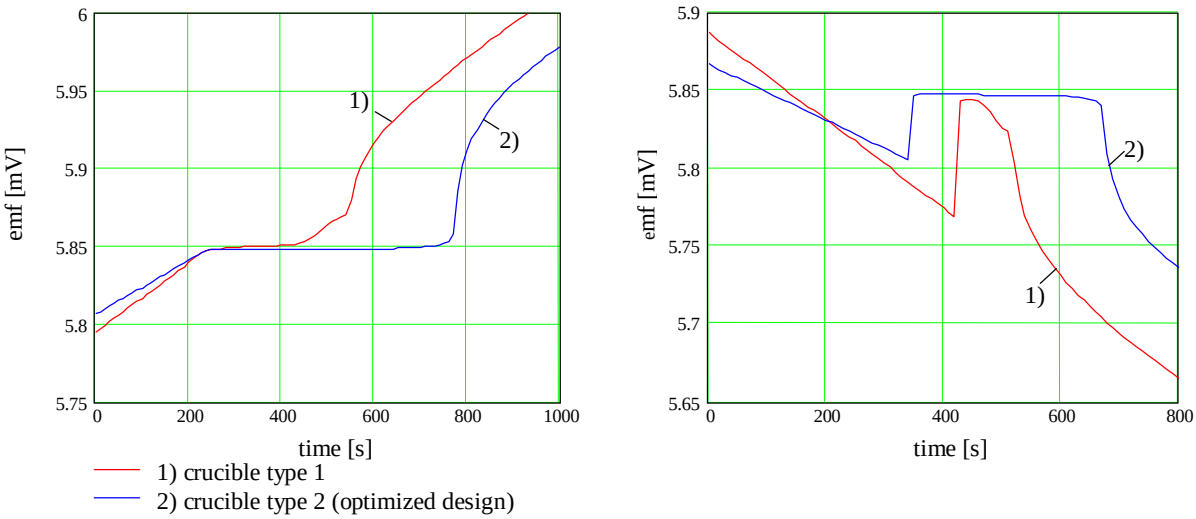


Figure 4: Melting and solidification plateaus of aluminium at rates of change of the temperature of 1 K/min in miniature fixed-point crucibles of a conventional and an optimized design

3. EXAMPLES OF THE PRACTICAL APPLICATION IN THE SUPERHEATED STEAM RANGE OF POWER PLANTS

Sheathed thermocouples with miniature fixed-point cells had to undergo a life and a function test in three power plants. Table 1 shows the fixed-point materials used according to their steam temperatures and their temporal behaviour under different application conditions, and the calibration procedures [5, 6].

Table 1: Tested fixed-point materials for the application of miniature fixed-point thermocouples in the superheated steam range in power plants

Steam temperature	Mode of operation	Fixed-point material	Fixed-point temperature t_{90}
535 °C	without heating	Cu/Sb (23 wt% of Cu)	526 °C
535 °C	with heating	Al/Cu (67 wt% of Al)	548.16 °C
565 °C	with heating	Al/Si (87 wt% of Al)	577.2 °C
630 °C	with heating	Al	660.32 °C

For the time-dependent temperature changes necessary for carrying out a calibration process, we used in one case of application the periodic temperature behaviour, conditioned by the process itself, resulting from the regular starting and shutting-down processes between partial load and full load.
In order to be able to set off calibration processes externally also in the other cases of application at a steam temperature which is nearly constant over a longer time period, an electrical heating element consisting of a metal foil and cylindrically arranged around the miniature fixed-point cell was additionally inserted in the sheathed thermocouples. By applying an external drive, this permits to achieve temperature rises of the fixed-point material of about 20 to 40 K above the steam temperature, with the heating power ranging from 5 to 10 W. Furthermore, the rates of temperature rise of the miniature fixed-point cell can be adjusted between 0.2 K/min and 2 K/min.

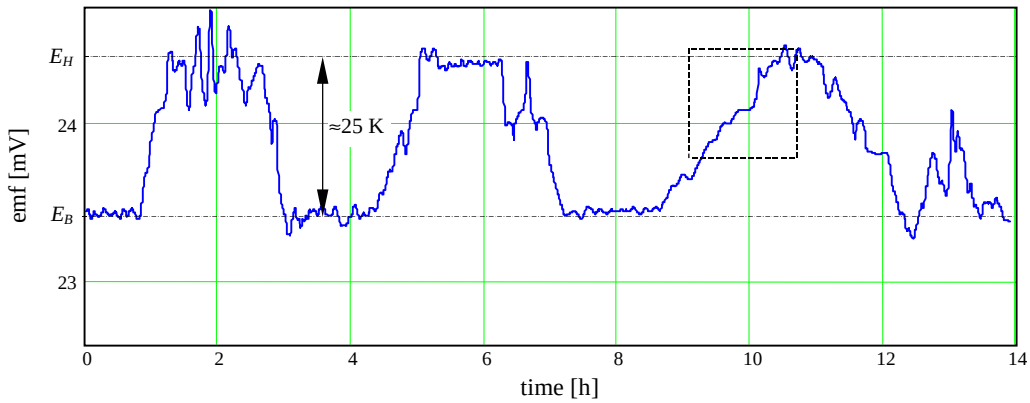


Figure 5: Real thermocouple emf behavior in a power plant with externally induced calibration processes

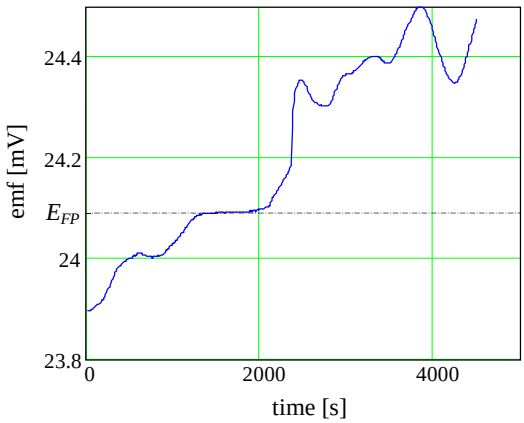


Figure 6: Melting plateau during the marked thermocouple emf behavior from Figure 5

In all four cases of application, the miniature fixed-point thermocouples have been fully functional for more than 12 months now. They have permitted to check the steam temperatures or also their temporal

drift measured by means of conventional working thermocouples in thermally identical protecting tubes and junctions.

4. CALIBRATION AND MEASUREMENT UNCERTAINTY ACHIEVABLE UNDER APPLICATION CONDITIONS

Under idealized conditions – time-linear temperature behavior in the measuring medium and in the fixed-point material during a sufficiently long plateau – the calibration point $E(T_{FP})$ is determined through straight line approximation (cf. Figure 1) [1]. Its uncertainty can be estimated in a relatively simple way [7].

However, in case of calibration processes which are greatly affected either electrically or thermally (as, for example, in industrial processes), and in case of a drift of the thermocouple characteristic or of other members of the measuring chain, an automatic computer-aided online recognition and evaluation of the calibration signals by means of disturbance-proof algorithms turns out to be necessary.

For this, a computer-aided measuring data processing on the basis of artificial neuronal networks is under development. This processing system searches for typical calibration signal patterns, identifies and classifies them, discriminates between usable and heavily disturbed calibration signals within the emf ranges to be expected, and finally determines a calibration value online. The first tests carried out with real emf curves measured using a suitable software yielded a portion of correctly identified and usable calibration processes of > 80 %. The error rate was negligible. Besides this, a single misinterpretation will be prevented by means of a plausibility test for the temporal behavior of the calibration values $E(T_{FP})$.

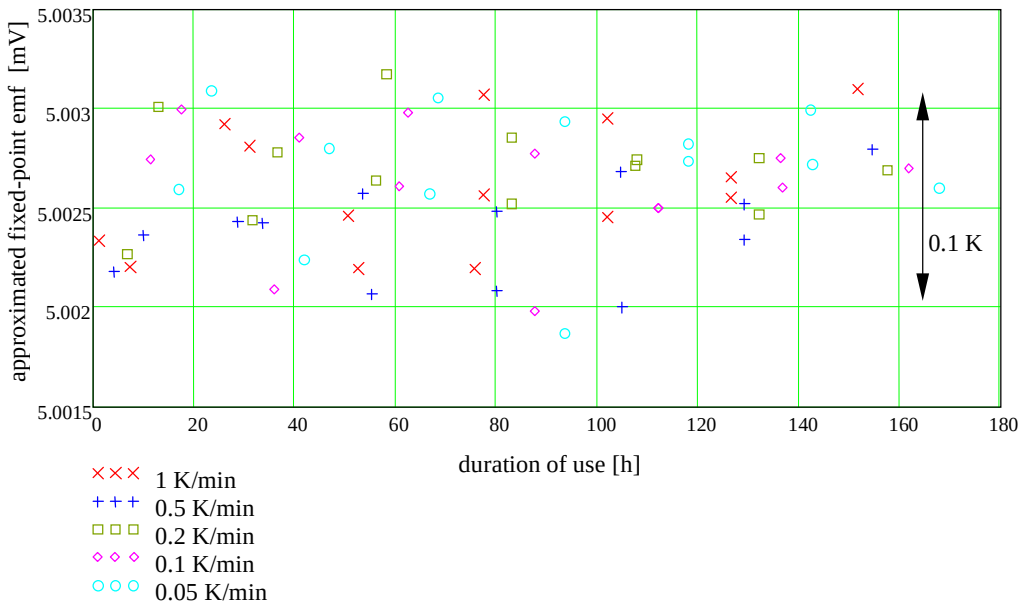


Figure 7: Typical reproducibility of the calibration results of a thermocouple type S with an miniature fixed-point cell under laboratory conditions

Regarding the reproducibility achieved of the calibration results in the range of 0.1 K with heated miniature fixed-point cells at very different heating rates under laboratory conditions, a calibration uncertainty at the fixed-point temperature of 0.3 K under power plant conditions can be expected.

Thus, the measuring uncertainty achievable at a temperature deviating from the fixed-point temperature can be estimated by combining the uncertainty to be expected at a parallel shift of the output characteristic by the calibration difference $E(T_{FP})$ and by assuming a second stable calibration value, in case of thermocouples, for example, E(0 °C). Thus, for a temperature measurement at 630 °C with a

thermocouple measuring chain regularly recalibrated at a temperature of $t_{90,Al}$=660.32 °C, an uncertainty of U(630 °C)= 0.5 K results.

5. SUMMARY AND AIMS

On the basis of practical tests carried out over more than one year in various power plants, it was possible to prove the long-term stability of the miniature fixed-point cells developed, the excellent reproducibility of their phase transformation temperatures, as well as the sufficient thermal and mechanical stressability of the miniature fixed-point sheathed thermocouples equipped with them.
The aim of these temperature sensors regarding their application in the superheated steam range in power plants is to reduce the current measuring uncertainty of temperature measuring chains of about 5 K to < 1 K by a periodic recalibration of the temperature sensors and of the subsequent measuring chain under application conditions. Furthermore, a higher degree of efficiency and lower CO_2 emissions shall be obtained at the same maximum admissible temperatures of piping systems and fittings.

ACKNOWLEDGEMENTS

The authors wish to thank the German Federal Ministry for Science and Technology, the project sponsor BEO, the German Federation of Industrial Cooperative Research Associations (Arbeitsgemeinschaft industrieller Forschungsvereinigungen e.V., AiF), the Technical Association of Large Power Plant Operators (Vereinigung der Großkraftwerkbetreiber VGB), the power plants Neckarwerke Stuttgart, Gemeinschaftskraftwerk Hannover and Hamm/Westfalen, as well as the companies RWE Power, electrotherm Geraberg and HTM Reetz Berlin for their financial support of the research projects (No. 0327066B/7 and No. 196/12132B/1) and the efficient cooperation.

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