Proc. Estonian Acad. Sci. Eng., 2007, **13**, 4, 320–337

In-situ calibration of inhomogeneous thermocouples by integrated miniature fixed-point cells

Frank Bernhard

Ilmenau University of Technology, D-98684 Ilmenau, Germany; frank.bernhard@tu-ilmenau.de

Received 26 October 2007

Abstract. According to the gradient theory, the emergence of the thermovoltage takes place only in sections of the thermocouple with temperature gradient. It is shown that, in the case of inhomogeneous thermocouples, the thermovoltage measured does not depend only on the temperatures of hot and cold junctions, but also on the temperature profile alongside the thermocouple. As in the case of an external calibration the temperature profile is never the same as in the real application, any correction of inhomogeneous thermocouples based on it will be imperfect. However, thermocouples with integrated miniature fixed-point cells allow also in case of inhomogenity a correct and automatic in-situ calibration. The paper describes the structure and mode of operation of such thermocouples and reports on the experience of their application in the hot-steam area of power stations.

Key words: thermovoltage, thermocouple, calibration, inhomogeneity, fixed point.

1. INTRODUCTION

"Thermocouples are the most often used, the most misrepresented, and so the most widely misunderstood sensors of thermometry" [1]. There are two main reasons for this. On the one hand, thermocouples tend to present material changes which are inhomogeneously distributed along their length during application, leading to characteristic drifts. On the other hand, the fact that in the case of inhomogeneous thermocouples the thermovoltage measured does not depend only on the temperatures of the hot and cold junctions, but also on the temperature response alongside the thermocouple, is often ignored [2].

From the so-called gradient theory of the emergence of the thermovoltage, which is described in a simplified way below, conclusions can be drawn concerning the calibration errors that can arise in the case of an external recalibration of inhomogeneous thermocouples.

Finally, the use of integrated miniature fixed-point cells is described, which allows an in-situ recalibration with very low uncertainty of inhomogeneous thermocouples with a characteristic drift under operating conditions.

2. PROBLEMS ARISING DURING THE CALIBRATION OF INHOMOGENEOUS THERMOCOUPLES

2.1. Gradient theory of the emergence of the thermovoltage

For the internal energy W of a closed thermocouple circuit in its stationary state with a current intensity I during the time t, the following equation can be set up according to the first law of thermodynamics:

$$\oint \mathrm{d}W = [\pi_{\mathrm{A/B}}(T_{\mathrm{M}}) - \pi_{\mathrm{A/B}}(T_{\mathrm{V}}) - \int_{T_{\mathrm{V}}}^{T_{\mathrm{M}}} (\tau_{\mathrm{A}} - \tau_{\mathrm{B}})\,\mathrm{d}T - U_{\mathrm{A/B}}(T_{\mathrm{M}}, T_{\mathrm{V}})]\,It = 0. \qquad (1)$$

From Eq. (1), a relationship between the thermovoltage $U_{\mathrm{A/B}}$ and the “hot” junction temperature T_{M} and the “cold” junction temperature T_{V} according to the Seebeck effect, can be derived [3]:

$$U_{\mathrm{A/B}}(T_{\mathrm{M}}, T_{\mathrm{V}}) = \pi_{\mathrm{A/B}}(T_{\mathrm{M}}) - \pi_{\mathrm{A/B}}(T_{\mathrm{V}}) - \int_{T_{\mathrm{V}}}^{T_{\mathrm{M}}} (\tau_{\mathrm{A}} - \tau_{\mathrm{B}})\,\mathrm{d}T. \qquad (2)$$

Here $\pi_{\mathrm{A/B}}$ is the Peltier coefficient and τ_{A} and τ_{B} are the Thomson coefficients.

This equation has been mistakenly regarded as a definition of the thermovoltage and the conclusion has been drawn that the thermovoltage $U_{\mathrm{A/B}}$ is composed mainly of the voltages $\pi_{\mathrm{A/B}}(T_{\mathrm{M}})$ and $\pi_{\mathrm{A/B}}(T_{\mathrm{V}})$ developing at the junctions with temperatures T_{M} and T_{V}, and to a smaller part of the voltages $\int \tau_{\mathrm{A}}\mathrm{d}T$ and $\int \tau_{\mathrm{B}}\mathrm{d}T$, resulting from temperature gradients in the thermowires. However, the thermovoltage is also measured when the circuit is open, i.e. when $I = 0$, where neither Peltier nor Thomson effects occur (which are sheer current effects) [4,5].

In contrast to this, modern gradient theory says that the thermovoltage $U_{\mathrm{A/B}}$ of a thermocouple from materials A and B results from the integration of differential partial voltages $\mathrm{d}U$ alongside both thermoelectric legs, which are proportional to the local temperature gradient $\mathrm{d}T/\mathrm{d}z$ [6,7]:

$$\mathrm{d}U_{\mathrm{A/B}}(T, z) = S_{\mathrm{A/B}}(T, z)\frac{\partial T}{\partial z}. \qquad (3)$$

Assuming at first single, relatively short sections Δz alongside the thermocouple (Fig. 1), the partial thermovoltages $U_{\mathrm{A},i}$ and $U_{\mathrm{B},i}$ of the legs A and B,

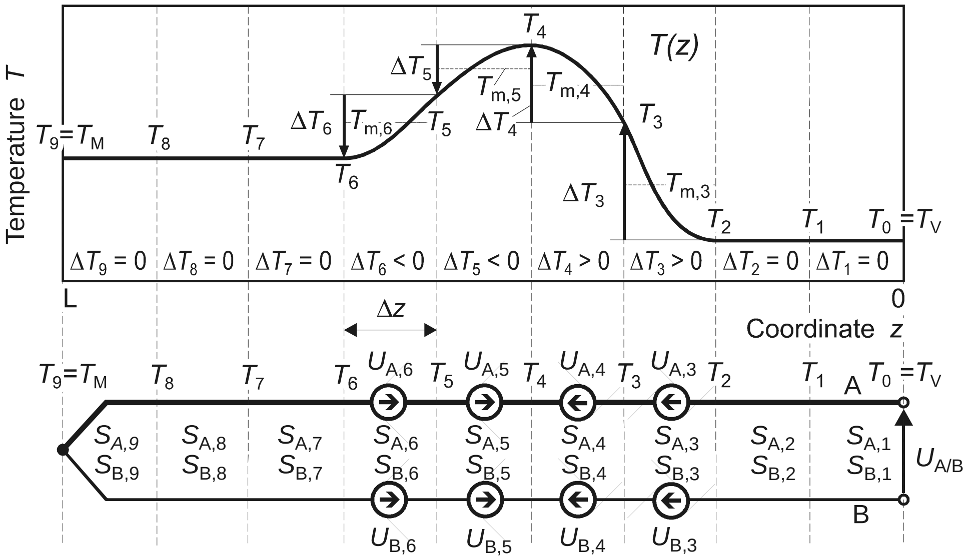

Fig. 1. Schematic, illustrating the gradient theory of the emergence of the thermovoltage: equivalent circuit of a thermocouple, made of the materials A and B at a temperature profile $T(z)$ with effective temperature gradients in the sections 3 to 6.

arising in section i, can be calculated from the Seebeck coefficients $S_{A,i}$ and $S_{B,i}$, at the mean temperature $T_{m,i}$ and the temperature difference ΔT_i over this section:

$$U_{A,i} = S_{A,i}(T_{m,i})\Delta T_i, \quad U_{B,i} = S_{B,i}(T_{m,i})\Delta T_i. \tag{4}$$

Thus because of the formation of the difference between $U_{A,i}$ and $U_{B,i}$ in the circuit, the partial thermovoltage $U_{A/B,i}$ in section i amounts to

$$U_{A/B,i} = [S_{A,i}(T_{m,i}) - S_{B,i}(T_{m,i})]\Delta T_i = S_{A/B,i}(T_{m,i})\Delta T_i. \tag{5}$$

Since

$$\Delta T_1 = \Delta T_2 = \Delta T_7 = \Delta T_8 = \Delta T_9 = 0, \tag{6}$$

the total thermovoltage $U_{A/B}$, prevailing at the temperature profile $T(z)$ shown, amounts only to the sum of the partial thermovoltages of sections 2–6:

$$U_{AB} = \sum_{i=3}^{6} U_{A/B,i}. \tag{7}$$

Taking into account Eq. (3), Eq. (5) can be written as

$$U_{AB}\Big|_0^L = \int [S_A(T,z) - S_B(T,z)] \frac{\partial T}{\partial z}\, dz = \int_0^L S_{AB}(T,z) \frac{\partial T}{\partial z} dz. \tag{8}$$

Assuming that materials are homogeneous, i.e.

$$S_{\mathrm{A/B}}(T, z) = S_{\mathrm{A/B}}(T) \neq f(z), \tag{9}$$

Eq. (8) takes on the following simplified form:

$$U_{\mathrm{A/B}}(T_{\mathrm{M}}, T_{\mathrm{V}}) = \int_{T_{\mathrm{V}}}^{T_{\mathrm{M}}} S_{\mathrm{A/B}}(T)\,\mathrm{d}T. \tag{10}$$

Thus in the case of homogeneous thermocouples, the temperature profile $T(z)$ alongside the thermocouple between the junctions with temperatures T_{M} and T_{V} has no influence on the thermovoltage measured [[8]].

2.2. Characteristic drift and inhomogeneity

Any time- and temperature-dependent deviations $\Delta U_{\mathrm{A/B}}(T, t)$ of the output voltage of a thermocouple from a standard or calibration value $U_{\mathrm{A/B}}(T_{\mathrm{M}}, T_{\mathrm{V}})$, occurring during operation (characteristic drifts), are practically always accompanied by local changes in the Seebeck coefficients $S_{\mathrm{A}}(T, t, z)$ and $S_{\mathrm{B}}(T, t, z)$ of just one or both thermoelectric legs, occurring at locally different points over the length of the thermocouple, i.e. between the junctions with the temperatures T_{M} and T_{V}. They can be caused by

– the absorption of substances from the environment of the thermocouple by dissolution or chemical reactions,
– the loss of alloying constituents due to selective evaporation or chemical attacks,
– recrystallization and ordering effects,
– the mutual diffusion of the leg materials on both sides of the "hot" junction.

Furthermore, a change in the thermovoltage measured is caused by

– local reductions in the insulation resistance between the thermowires themselves and from the thermowires to the sheath or also to the protecting tube at higher temperatures, or by moisture effects and mechanical impacts,
– local parasitic galvanic voltage sources between the thermowires themselves and to the sheath or also to the protecting tube due to moisture diffusion.

The following factors influence the magnitude of the changes in the Seebeck coefficients or also in thermovoltage measured:

– temperature, temperature variation with time, local temperature profile alongside the thermocouple,
– time of operation of the thermocouple or the duration of the effect of the factors mentioned above,
– design and materials of the thermocouple and of the temperature measuring point,
– diameter of the thermowires,
– chemical corrosivity of the measuring medium or of the environment with regard to the materials the thermocouple is made of.

2.3. Examples of thermocouple drifts

In the technical literature, a large number of publications can be found giving more or less detailed information on the characteristic drift of thermocouples of various types and designs at different temperatures and operation conditions. This information can be generalized or also applied to a concrete application only in a very restricted way for the following reasons.

1. The mechanisms of action, which cause a characteristic drift and which determine its magnitude and variation with time, are both type- and specimen-specific.
2. Depending on the temperature range and the temperature variation with time and under different operation conditions even thermocouples of the same batch present in some cases a hardly comparable drift behaviour.
3. Most publications do not contain any information on the local inhomogeneities of the thermocouple examined, which are always closely connected with a characteristic drift.
4. Also the methods applied for recalibration (in-situ methods, tests in special calibration devices) yield different results or cause a change in the inhomogeneity distribution and in the characteristic behaviour, or also modify the ageing process of the thermocouple.

However, some selected examples of investigations of thermocouple drifts are described below. Figure 2 shows typical temperature measuring errors due to a characteristic drift of different thermocouples after a time of operation of more than 1000 h as a function of the operating temperature in the logarithmic scale. From (Fig. 2), a simple and relatively generally valid basic rule can be derived: the higher the melting point of the material, the lower the characteristic drift at the same temperature and time of operation [9].

The dependence of the drift measuring error δT on the temperature can obviously be approximated (for the tungsten/rhenium and the iron/copper-nickel thermocouples investigated) by an exponential function

$$\delta T(T)_{t=1000\,\mathrm{h}} = \mathrm{a}\,\mathrm{e}^{bT}. \tag{11}$$

Figure 3 shows, in contrast to Fig. 2, negative characteristic drift of a NiCr/NiAl thermocouple with a diameter of 0.8 mm in a slightly carburizing atmosphere of 95% CO_2 and 5% CO at a temperature of 850 °C as a function of the operating time.

As under constant operation conditions a characteristic drift normally is a continuous function, even approaching a stable final state, in some cases it is possible to derive from regular recalibrations a practical time-dependent drift model [9].

Thus, for this case, it can also be approximated by an exponential function of the type

$$\delta T(t)_{T=850\,^\circ\mathrm{C}} = \mathrm{a}\,\mathrm{e}^{bT}. \tag{12}$$

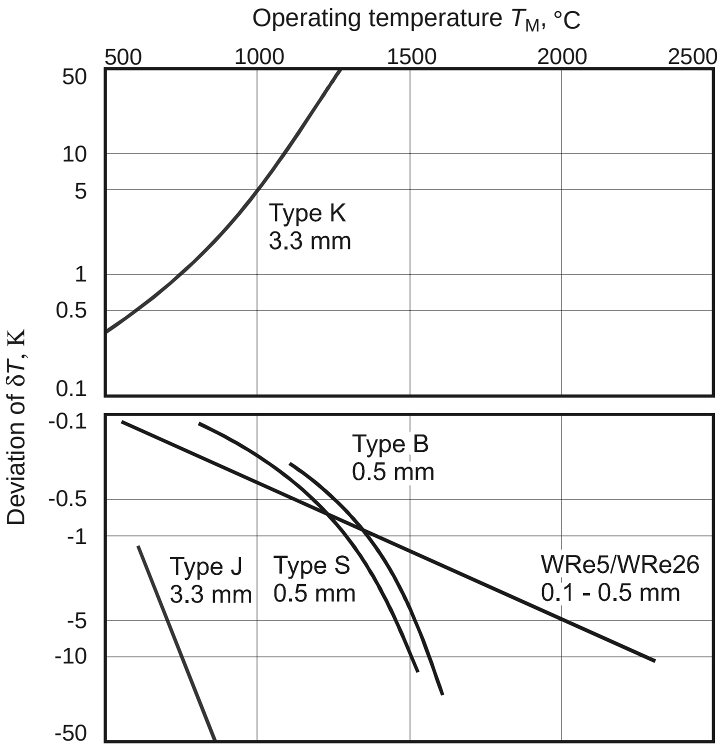

Fig. 2. Average characteristic drift after 1000 h of operation as a function of the operating temperature; parameter: diameter of the thermowire [9].

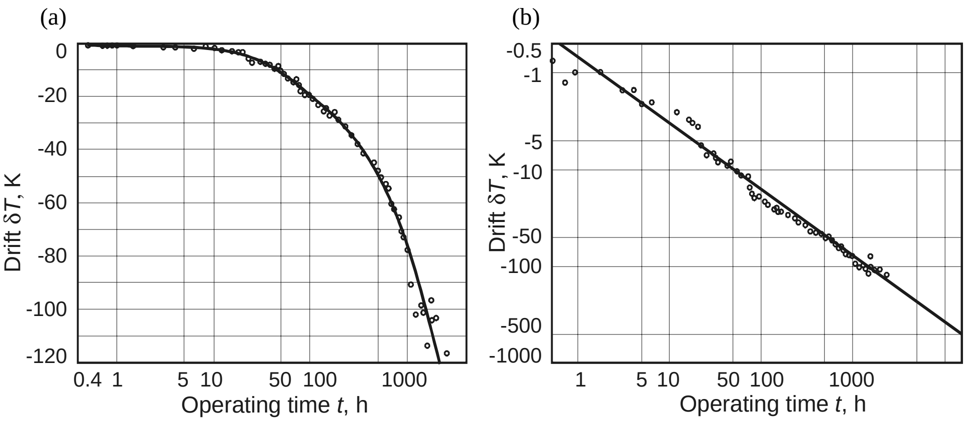

Fig. 3. Ageing of a NiCr-NiAl thermocouple (type K, 0.8 mm Ø) at an operating temperature of T_M = 850 °C [9]: (a) linear scale; (b) logarithmic scale.

Although this function allows in many cases approximationed of the variations of thermocouple drifts with time, due to ageing processes it can be applied, like Eq. (11), to other thermocouples with restrictions.

The application of this model for predicting drift values, with the aim to realize a time-dependent controlled correction without any further recalibration, can be recommended only in exceptional cases, with experimentally well established measuring values for thermocouples of one type, of the same design and batch, and under constant and identical application conditions.

2.4. Practical consequences for the calibration and recalibration of inhomogeneous thermocouples

For checking the characteristic drift, occurring during operation, or also for its correction by calculations, a thermocouple can be removed and recalibrated externally. Due to the fact that the characteristic drift of a thermocouple is always connected with inhomogeneities and that the temperature profile alongside the thermocouple found in the calibration device is not the same as in the application, these calibration results can be misleading. This shall be shown by means of a simplified equivalent circuit for an inhomogeneous thermocouple at different temperature profiles $T(z)$ in an application case, and $T_{\text{cal,1}}(z)$ and $T_{\text{cal,2}}(z)$ for an external calibration.

The fundamental effects of the inhomogeneity of a thermocouple, i.e., of local deviations $\Delta S_{\text{A/B,I}}(T_{\text{m},i})$ of the Seebeck coefficient from a standard or default value $S_{\text{A/B}}(T_{\text{m},i})$, can again be represented, similarly to the way shown in Fig. 1, by means of an electric equivalent circuit (Fig. 4).

The total thermovoltage of an inhomogeneous thermocouple

$$U_{\text{A/B}}\Big|_0^{\text{L}} + \Delta U_{\text{A/B}}\Big|_0^{\text{L}} = \sum_{i=0}^{n}\{[S_{\text{A/B}}(T_{\text{M},i}) + \Delta S_{\text{A/B},i}(T_{\text{M},i})]\Delta T_i\} \tag{13}$$

can be described as the sum of the thermovoltage of a homogeneous thermocouple with the temperature-dependent, but locus-independent standard values according to Eq. (4) or (7):

$$U_{\text{A/B}}\Big|_0^{\text{L}} = \sum_{i=0}^{n} S_{\text{A/B}}(T_{\text{m},i})\Delta T_i = \sum_{i=3}^{6} S_{\text{A/B}}(T_{\text{m,i}})\Delta T_{\text{i}} \tag{14}$$

and a deviation thermovoltage $\Delta U_{\text{A/B}}(T_{\text{M}}, T_{\text{V}})$, resulting from local deviations of the Seebeck coefficient $\Delta S_{\text{A/B},i}(T_{\text{m},i})$:

$$\Delta U_{\text{A/B}}\Big|_0^{\text{L}} = \sum_{i=0}^{n} \Delta S_{\text{A/B}}(T_{\text{m},i})\Delta T_i = \sum_{i=3}^{6} \Delta S_{\text{A/B}}(T_{\text{m},i})\Delta T_i. \tag{15}$$

The local distribution of the sensitivity deviations $\Delta S_{\text{A/B}}(z)$ and $\Delta S_{\text{A/B},i}$, shown in Fig. 4, is based on the assumption that the inhomogeneity of the thermocouple, which has developed during operation, is roughly proportional to the temperature $T(z)$ or also $T_{\text{m},i}$.

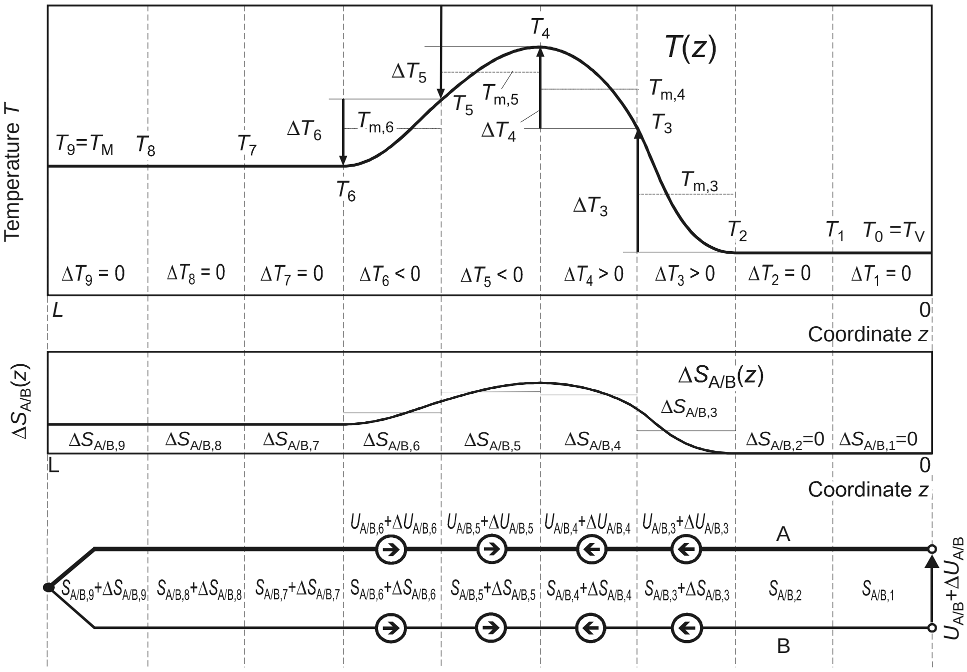

Fig. 4. Equivalent circuit of the thermocouple according to Fig. 1 with temperature-dependent inhomogeneities (inhomogeneously distributed drift portions $\Delta S_{\mathrm{A/B},i}$ and $\Delta U_{\mathrm{A/B},i}$) in sections 3 to 9 and effective temperature gradient in sections 3 to 6.

However, only the inhomogeneity or also the deviations $\Delta S_{\mathrm{A/B},i}$ of the Seebeck coefficient in sections $i=3$ to 6 are relevant to the resulting thermovoltage $(U_{\mathrm{AB}}+\Delta U_{\mathrm{AB}})\big|_0^{\mathrm{L}}$ because only in these sections a temperature gradient or also a temperature difference ΔT_i is present. For a recalibration, in turn, this means that only this thermovoltage deviation should be measured and corrected according to Eq. (15). For this, the temperature profile $T(z)$ used for recalibration should be the same as the one used in the application case.

External calibration devices, however, are usually structured so as to present an extended homogeneous temperature profile with a relatively steep temperature gradient beyond the calibration zone.

In the following, two examples of calibration profiles, $T_{\mathrm{cal},1}(z)$ and $T_{\mathrm{cal},2}(z)$, will be given to show that an external recalibration may yield values, which are basically incorrect for the particular application (Figs. 5, 6). In the case of $T_{\mathrm{cal},1}(z)$, only the last two sections of the thermocouple, 8 and 9, lie within the zone with the calibration temperature T_{cal}. Thus, the thermovoltage deviation measured

$$\Delta U_{\mathrm{A/B,cal,1}}\Big|_0^{\mathrm{L}}=\sum_{i=0}^{\mathrm{n}}\Delta S_{\mathrm{A/B}}(T_{\mathrm{m},i})\,\Delta T_i=\Delta S_{\mathrm{A/B}}(T_{\mathrm{m},7})(T_{\mathrm{cal}}-T_{\mathrm{V}}) \tag{16}$$

differs from the “true” correction value according to Eq. (14).

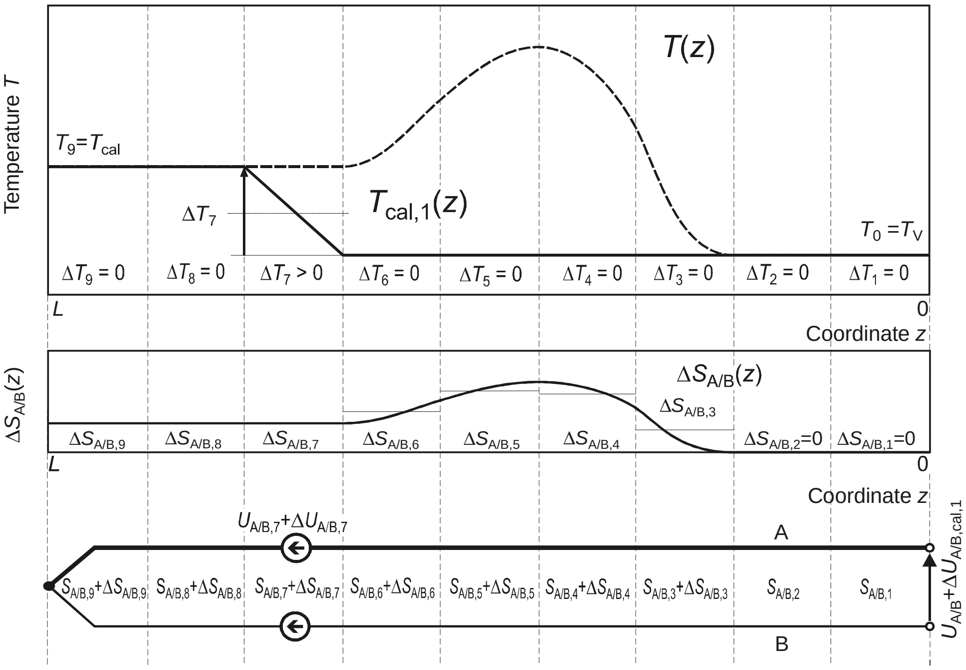

Fig. 5. Equivalent circuit of the inhomogeneous thermocouple according to Fig. 4 with temperature-dependent inhomogeneities (inhomogeneously distributed drift portions $\Delta S_{\mathrm{A/B},i}$ and $\Delta U_{\mathrm{A/B},i}$) in sections 3 to 9 at a calibration temperature profile $T_{\mathrm{cal,1}}(z)$ with an effective temperature gradient in section 7.

In the case of the second example of a temperature profile, $T_{\mathrm{cal,2}}(z)$, all inhomogeneous sections are located in the zone with the calibration temperature. Thus no thermovoltage deviation is present:

$$\Delta U_{\mathrm{A/B,cal,2}}\Big|_0^{\mathrm{L}} = \sum_{i=0}^{\mathrm{n}} \Delta S_{\mathrm{A/B}}(T_{\mathrm{m},i})\Delta T_i = \Delta S_{\mathrm{A/B}}(T_{\mathrm{m,2}})\Delta T_2 = 0. \tag{17}$$

Furthermore, an external recalibration changes the ageing and also drift process of the thermocouple under application conditions. Thus an in-situ recalibration, carried out under application conditions on the basis of a measurement using a reference temperature sensor, is useful. This, however, presupposes parallel measuring points of the same type and temperature. Another possibility, even though a very complex one, is to combine a thermocouple with a noise resistance. This alternative was developed for high-temperature measurements, made primarily in the field of nuclear technology [[10]].

A possibility, which has been successfully tested and utilized so far in industry, is offered by thermocouples with integrated miniature fixed-point cells. They allow the user to determine their current output quantity or also read-out over the entire measurement sequence at an exactly known sensor temperature

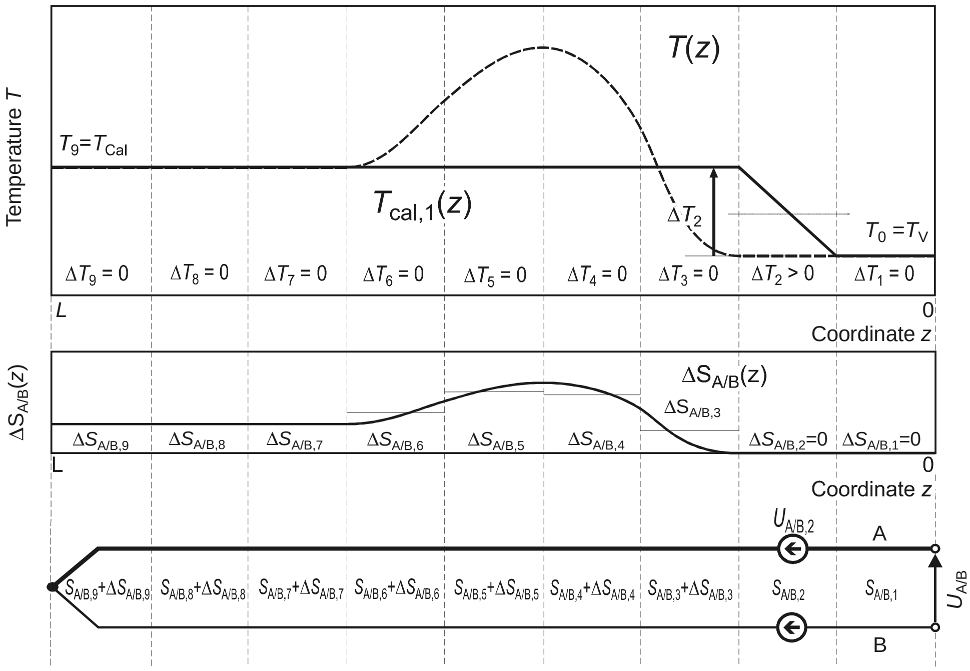

Fig. 6. Equivalent circuit of the inhomogeneous thermocouple according to Fig. 4 with temperature-dependent inhomogeneities (inhomogeneously distributed drift portions $\Delta S_{\mathrm{A/B},i}$ and $\Delta U_{\mathrm{A/B},i}$) in sections 3 to 9 at a calibration temperature profile $T_{\mathrm{cal},2}(z)$ with an effective temperature gradient in section 2.

and, thus, to correct a drift of the thermocouple and of other elements of the measurement sequence for this temperature [11].

3. THERMOCOUPLES WITH INTEGRATED MINIATURE FIXED-POINT CELLS

3.1. Basic principle

The basic principle of self-calibrating thermocouples consists in integrating a suitable fixed-point material, encapsulated in a miniature fixed-point cell, into a thermocouple (Fig. 7). When the temperature around the melting or also freezing temperature T_{FP} of the fixed-point material changes, the thermoelectric voltage undergoes characteristic temporal variations due to phase transformations (Fig. 7). From these characteristic temporal changes, a calibration value $U(T_{\mathrm{FP}})$ for the thermocouple or also for the entire measuring sequence can be obtained at the fixed-point temperature [12].

To make this principle usable on an industrial scale for the automatic in-situ recalibration of thermocouples under operating conditions, such as in power plants, the following preconditions are to be fulfilled [12]:

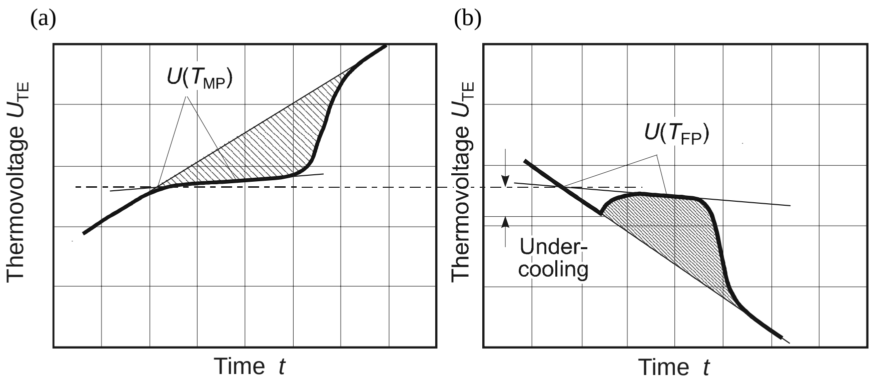

Fig. 7. Thermovoltage profiles of a thermocouple in a miniature fixed-point cell during melting (a) and freezing (b) processes.

– long-term stability of the miniature fixed-point cells also in case of temperatures and temperature cycles far above the phase transformation temperature;
– availability of small and metrologically optimum fixed-point cells, which permit integration into industrial gauge inserts;
– availability of fixed-point materials with well reproducible phase transformation temperatures at a small distance to the normal operating temperature of the thermocouple to guarantee an as low as possible measuring uncertainty after a single-point calibration.

3.2. Technical realization in power plants

When selecting suitable substances as fixed-point materials, four aspects should particularly be considered:

– phase transformation temperature at normal pressure of about 20 to 50 K above the normal operating temperature,
– material available of sufficient purity (>99.99%),
– ratio between enthalpy,
– latent heat during phase transformation.

In cooperation with several large power plants, probes, which fulfilled these requirements, were developed and tested under practical application conditions. In doing so, a total of 6 different technically pure metals and binary alloys, whose phase transformation temperatures lie in the temperature range of the superheated steam, were successfully employed (Table 1).

Table 1. Usable fixed points for superheated steam temperature [13]

Alloy	T_{FP}, °C	Alloy	T_{FP}, °C
Pb	327.5	Al87Si	578.7
Al67Cu	548.2	Al75Pd	616.5
Ag71Al	567.6	Al	660.3

The miniature fixed-point crucible to be integrated into the complete thermocouple must contain the fixed-point material and prevent permanently foreign substances from penetrating, or also any chemical changes. The crucible material must meet the following requirements:

– temperature stability in the air at working temperatures,
– chemical long-term stability against metal melts,
– availability and processability at high purity,
– high thermal conductivity and low thermal capacity.

Thus various ceramic materials such as aluminium oxide, silicon nitride, boron nitride, and aluminium nitride have proved to be suitable crucible materials.

A controllable heating element, additionally integrated into the thermocouple, makes it possible to calibrate the entire measuring sequence from outside also in case of constant medium temperature (Fig. 8). During practical application, a calibration uncertainty at the fixed-point temperature of about 0.2 K and measuring uncertainties at the operating temperature less than 1 K are obtained.

In the case of conventional steam generators in power plants, equipped with thermocouples of the K or N type, a drift of their characteristics and error limits, is to be expected with the uncertainty being up to 5 K. The aim is to reduce the necessary safe distance between the controlled steam temperature and the maximum permissible temperatures for pipelines and plumbing controls by a considerably lower uncertainty, thus permitting a higher efficiency ratio and lower amounts of emissions to be reached (Fig. 9).

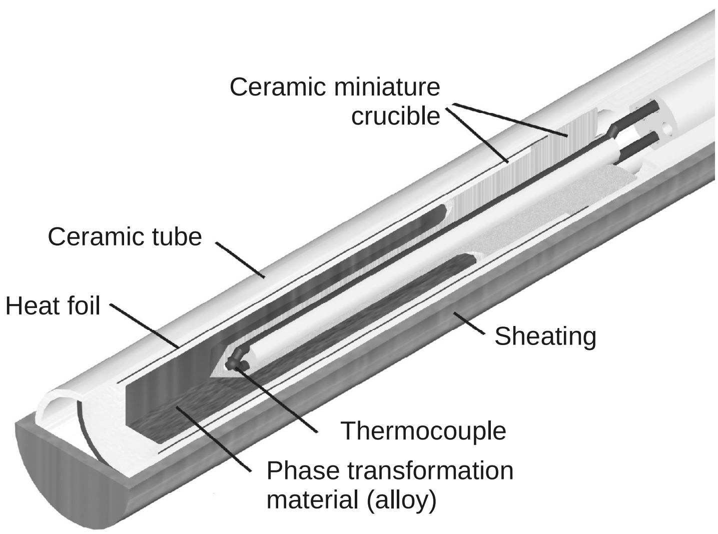

Fig. 8. Structure of a miniature fixed-point thermocouple with integrated heating of external diameter 6 mm.

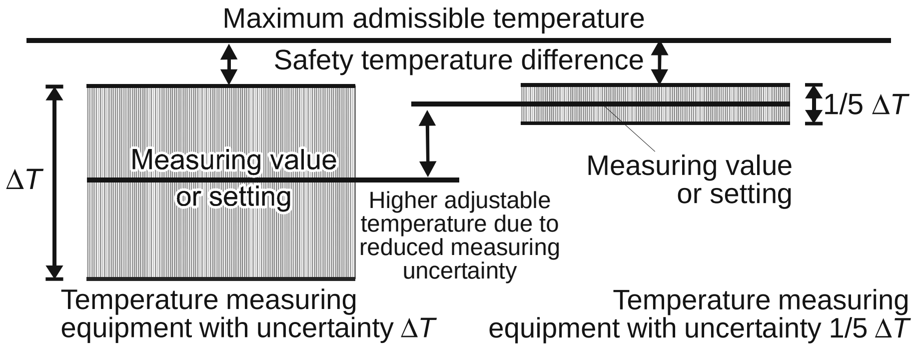

Fig. 9. Schematic representation of the connection between temperature measurement uncertainty and the adjustable desired temperature.

3.3. Test results

During test runs during over more than 15 000 operating hours performed in various power plants under different application conditions, it was possible to prove the serviceability and the long-term stability of the miniature fixed-point cells developed. Excellent reproducibility of phase transformation temperatures and sufficient thermal and mechanical load capacity of the miniature fixed-point sheathed thermocouples equipped with these fixed-point cells were also observed.

Figure 10 shows calibration cycles, measured for a thermocouple with Al fixed-point cell, in a power plant at a steam temperature of 630 °C.

By means of the local miniature heatings, integrated into the MFP thermocouples, it was possible to achieve temperature variations (which were time-linear on average) of the fixed-point cell of up to 30 K at temperature variation rates between 0.1 and 1 K/min. The induced phase transformation plateaus proved to be extremely reproducible both with regard to their shapes and fixed-

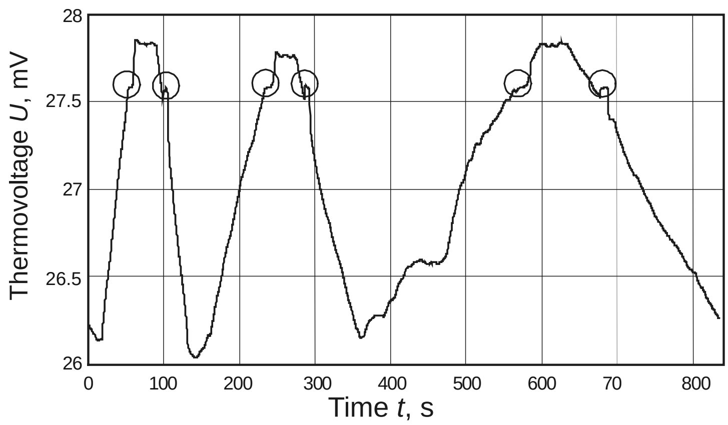

Fig. 10. Typical calibration cycles in the temperature range of 630 °C (steam temperature) and 660 °C (fixed-point temperature of Al, thermocouple type K).

point temperatures, approximated from them. No significant dependence of the fixed-point temperatures on the heating or cooling rate was observed (Figs. 10 to 12).

For the automatic recognition and evaluation, affected by superposed variations of the steam temperature in a real application (Fig. 12), algorithms have been developed, which yield well reproducible calibration values in more than 90% cases of calibration processes in various power plants.

Figure 13 shows the result obtained in a long-time application. The solid curve represents the apparent temporal variation of the fixed-point temperature, measured with a thermocouple, first not calibrated and not corrected. It thus represents the drift of the thermocouple and of the entire measurement sequence.

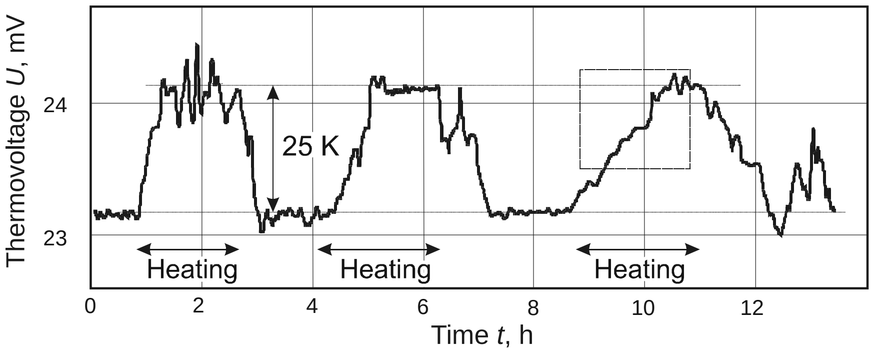

Fig. 11. Typical calibration cycles when using an integrated miniature heating at steam temperatures of about 565 °C and varying heating power (thermocouple type K).

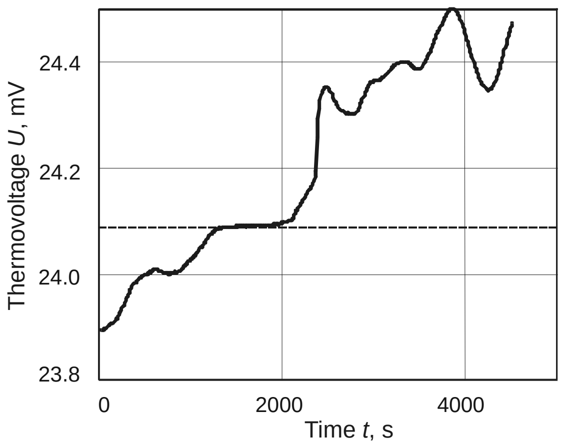

Fig. 12. Single typical thermovoltage behaviour from Fig. 11 during a calibration process with superposed process-dependent temperature variations (thermocouple type K).

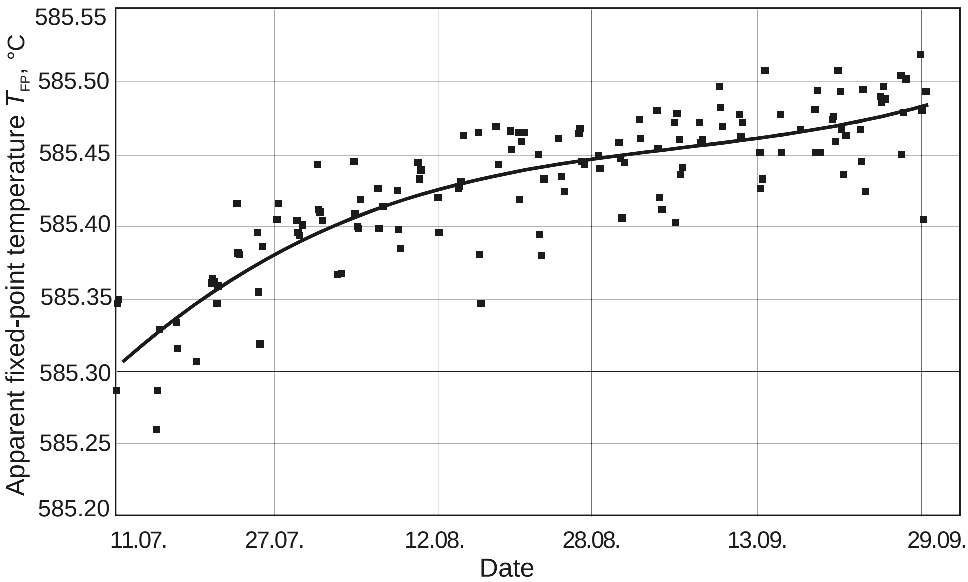

Fig. 13. Typical behaviour of the long-time calibration of a thermocouple measurement sequence in the superheated steam area (thermocouple type N).

The variance obtained for the single calibration values proves good reproducibility both of the actual thermovoltage measurement and of the evaluation method for the melting and freezing processes for in-situ calibration under power plant conditions. In addition, the smoothness of the averaged curve and the variance of single values are a useful measure of the measurement uncertainty of the overall set-up.

3.4. Long-time stability

After an operation time of more than one year, the test thermocouple was checked in the calibration laboratory. The results are illustrated in Fig. 14. It can be seen that the measured fixed-point plateaus can still be evaluated without any problems. The fixed-point temperature, which can be found, has changed by less than 100 mK. The visible difference between the two curve shapes is caused by the drift of the thermocouple to be corrected.

As for the freezing temperature of the material (aluminium) in the miniature fixed-point cell, one can start with the assumption that it has changed only slightly during the long-term measurements under power plant conditions. Comparative measurements of the miniature fixed-point thermocouple, made in a standard reference aluminium fixed-point cell, yielded, from the thermoelectric voltage profile, a difference of about –70 mK between the short miniature fixed-point freezing plateau (Fig. 15, right-hand part of the curve) and the long reference freezing temperature plateau (Fig. 15, left-hand part of the curve).

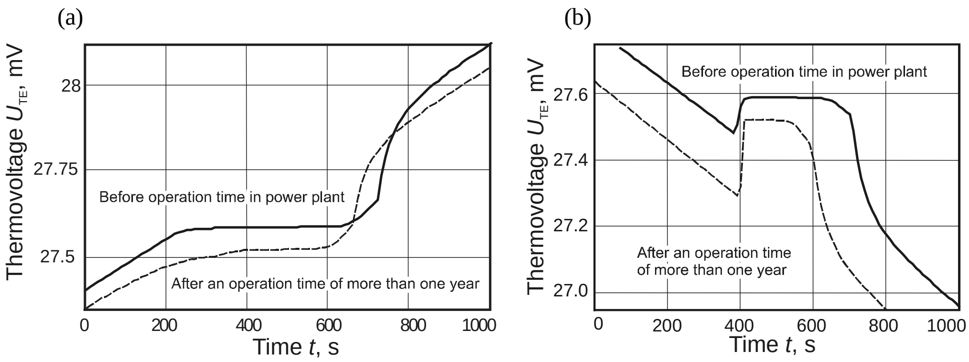

Fig. 14. Melting (a) and freezing (b) plateaus before and after long-time application under power plant conditions (thermocouple type N).

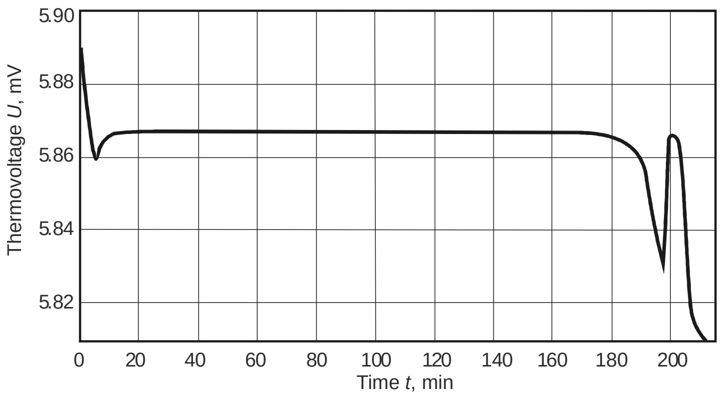

Fig. 15. Freezing plateaus of a reference aluminium fixed-point cell (T_{FP} = 660.323 °C) and of the aluminium miniature fixed-point cell in the MFP-thermocouple type N after long-time operation at steam temperatures of 630 °C.

Further long-term measurements were carried out in several power plants using metal alloys as the fixed-point material [14,15].

During these test measurements, made over more than one year at steam temperatures of 535 and 565 °C, no significant changes of the miniature fixed-point plateaus of an Al67/Cu thermocouple, measured at a temperature of 548.2 °C, or of an Al87/Si thermocouple at a temperature of 577.2 °C, were observed. The miniature cells, heating systems and thermometer designs used showed a high thermal and mechanical long-term stability.

4. SUMMARY

Starting from the gradient theory of the emergence of the thermovoltage in the sections alongside a thermocouple with a temperature gradient, and from the connections between the characteristic drift and the development of inhomogeneities, this paper shows that a classical recalibration of inhomogeneous thermocouples in an external calibration device with a different temperature profile may lead to calibration errors. A nearly exact single-point recalibration, using the temperature profile of the application, is possible by employing miniature fixed-point cells, integrated into the thermocouple. Their structure and application is described.

REFERENCES

1. Reed, R. P. Possibilities and limitations of self-validation of thermoelectric thermometry. In *Temperature, Its Measurement and Control in Science and Industry*. American Institute of Physics, 2003, vol. 7, 507–512.
2. Bernhard, F. (ed.). *Technische Temperaturmessung*. Springer-Verlag, Berlin, 2004.
3. Henning, F. and Moser, H. (eds.). *Temperaturmessung*, 3rd ed. Johann Ambrosius Barth, Leipzig, 1977.
4. White, W. P. What is the most important portion of a thermocouple? *Phys. Rev.*, 1908, **32**, 535–536.
5. Brixy, H. Thermocouple thermometry. *ISOTECH J. Thermometry*, 1995, **6**, H. 1, 1–17.
6. Quinn, T. J. *Temperature*, 2nd ed. Academic Press, London, 1990.
7. Pollock, D.D. *Thermocouples, Theory and Properties*. CRC Press, Boca Raton, 1991.
8. Bentley, R. E. The distributed nature of EMF in thermocouples and its consequences. *Australian J. Instrumentation Control*, 1982, Dec., 128–132.
9. Körtvélyessy, L. *Thermoelement-Praxis – Neue theoretische Grundlagen und deren Umsetzung*, 3rd ed. Vulkan-Verlag, Essen, 1998.
10. Brixy, H., Hecker, R., Rittinghaus, K. F. and Höwener, H. Applications of noise thermometry in industry under plant conditions. In *Temperature, Its Measurement and Control in Science and Industry*. American Institute of Physics, 1982, vol. 5, part 2, 1225–1237.
11. Tischler, M. and Korembit, M. J. Miniature thermometric fixed points for thermocouple calibrations. In *Temperature, Its Measurement and Control in Science and Industry*. American Institute of Physics, 1982, vol. 5, part 1, 383–390.
12. Lehmann, H. and Bernhard, F. Self-calibrating thermocouples. In *Proc. 6th International Symposium on Temperature and Thermal Measurements in Industry and Science*. Torino, 1996, 195–206.
13. Boguhn, D., Augustin, S., Bernhard, F., Mammen, H. and Tischler, M. Application of binary alloys in miniature fixed-point cells as secondary fixed points in the temperature range from 500 °C to 660 °C. In *Temperature, Its Measurement and Control in Science and Industry, 8th Symposium*. Chicago, 2002.
14. Augustin, S., Bernhard, F., Boguhn, D., Donin, A. and Mammen, H. Industrial applicable miniature fixed-point thermocouples. In *Proc. 8th International Symposium on Temperature and Thermal Measurements in Industry*. Berlin, 2001, vol. 1, 3–8.
15. Bernhard, F., Boguhn, D., Augustin, S., Mammen, H. and Donin, A. Application of self-calibrating thermocouples with miniature fixed-point cells in a temperature range from 500 °C to 650 °C in steam generators. In *Proc. XVII IMEKO World Congress on Metrology in the 3rd Millenium*. Dubrovnik, 2003, 1604–1608.

Mittehomogeensete termopaaride *in situ* kalibreerimine integreeritud miniatuursete fikseeritud rakukestega

Frank Bernhard

Mittehomogeensete termopaaride puhul ei sõltu genereeritav termopinge mitte ainult kuuma ja külma ühenduskoha temperatuurist, vaid ka temperatuuri jaotusest piki termopaari. Kuna see jaotus on muutlik, ei saa tavalisi kalibreerimismeetodeid kasutada. Lahendus on leitud fikseeritud rakukeste integreerimisega termopaari. Näitena on toodud temperatuuri mõõtmine soojuselektrijaama kuuma auru tsoonis.