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Fixed-Point Thermocouples in Power Plants: Long-Term Operational Experiences

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Abstract For more than four years, commercially available fixed-point thermocouples have measured hot-steam temperatures in power plants. A periodic self-adjustment procedure should keep their total measuring uncertainty within 1 K. This paper gives a short introduction to the measuring system components and their function. Despite heavy mechanical and thermal loads, the sensing elements show high reliability and appropriate availability. To evaluate the long-term reproducibility of the method, single thermometers have been dismantled and recalibrated in the laboratory at different time intervals. After more than 35 000 h of hard routine service the results have confirmed the expected uncertainty level.

Keywords Fixed-point thermocouples · Hot-steam temperature · *In-situ* calibration · Self-calibration · Self-adjustment

1 Introduction

The total measurement uncertainty for hot-steam temperatures of 500 °C to 600 °C in power plants is approximately 5 K. This value defines the customary safety margin with respect to the design temperature of the particular plant. Any degree of reduction of this uncertainty enables the hot-steam temperature to be increased adequately, which yields lower fuel costs and CO_2 exhaust per power unit. Basic investigations mainly carried out in the past at the Ilmenau University of Technology showed that miniature fixed-point crucibles integrated into thermocouples can reduce their total uncertainty to 1 K. Laboratory and field tests have proven a reliable operation for more than one year [1–3]. Figure 1 outlines the special parts and dimensions of a fixed-point

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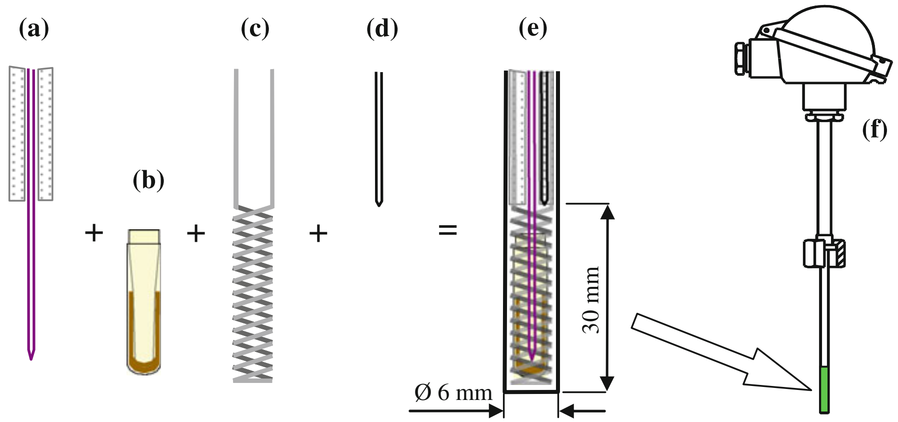

Fig. 1 Parts and their arrangement within the tip of a fixed-point thermocouple for hot-steam temperature measurements: (a) main (fixed-point) thermocouple TC1 (type N) in ceramic capillary, (b) ceramic fixed-point crucible with pure metal or eutectic alloy ingot, (c) miniature heating element, (d) second thermocouple TC2 for service (type N), (e) assembly in a stainless steel protecting tube, and (f) design of a complete measuring insert for installation in weld-in protection tubes

sensor as it has been commercially available since 2004 [4]. During more than four years of application in power plants, the reliability of the entire fixed-point thermocouple measuring system type SKTE2 has been proven. Laboratory recalibrations after long-term operation should support this result.

2 Fixed-Point Thermocouple Measuring System: Type SKTE2

2.1 Components and Interfaces

The SKTE2-system comprises up to eight fixed-point thermocouples as presented in Fig. 1. Each sensor is connected with a precision transmitter which supplies the miniature heater and measures the electromotive force of the thermocouples, as well as the cold-end junction temperature. One central master PC controls all data acquisition and adjustment procedures of the eight channels. To make the measuring and status variables available to the higher-level process control system of the power plant, different interfaces can be chosen. Furthermore, through ISDN, remote service and maintenance of the SKTE2-system are possible (Fig. 2). At the higher-level process control, each SKTE2-temperature is used as a reference variable for the on-line adjustment of conventionally designed hot-steam temperature measuring points. Usually, for a 100 % availability, the latter is a group of three mineral insulated metal-sheathed (MIMS) thermocouples (Fig. 3).

2.2 Self-Adjustment: How It Works

At least weekly, the Master PC starts a heating program which controls a multiple melting and freezing of the fixed-point substance (Fig. 4). Typically it comprises

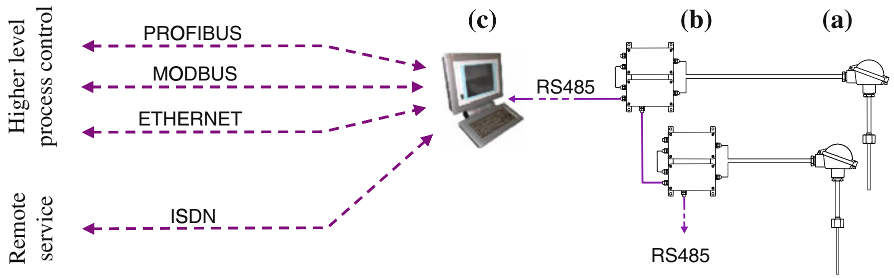

Fig. 2 Structure of a measuring system type SKTE2 (only two channels shown) and interfaces: (a) fixed-point thermocouples, (b) precision transmitters, and (c) master PC

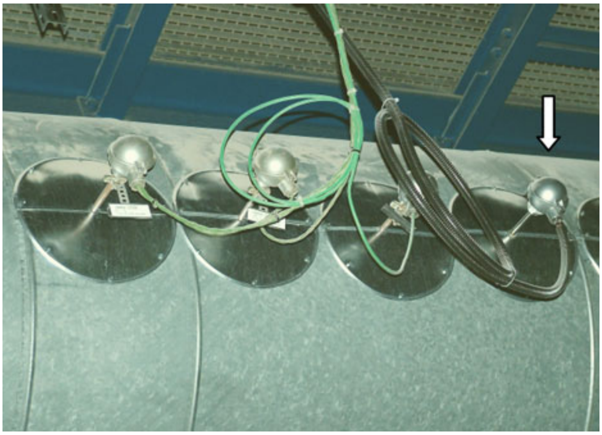

Fig. 3 Hot-steam pipeline with three redundant operating thermocouples and one fixed-point thermocouple of the SKTE2-system (*arrow*). Due to the improved accuracy of such combination, a power plant is allowed to operate 1 K below the upper layout temperature. The operation at 544 °C, instead of 540 °C in the past, for instance, yields savings of about 100 T€ fuel costs per year [5]

three complete smeltings with slightly different heating rates of about $1\,K \cdot min^{-1}$ to $2.5\,K \cdot min^{-1}$. This pure metal or eutectic alloy is selected from usable primary or secondary temperature fixed points having a phase change transition point about 10 K to 40 K above the particular hot-steam temperature [1,6].

After the last freezing, a signal analyzing algorithm looks for all sections within the recorded thermocouple signal presenting similarity to a melting plateau pattern. When the search is finished successfully, a set of signal characterizing parameters (cf. Fig. 4, on the right) will be calculated and stored in a history file (*self-calibration*). Only if all parameters fit into sensor-specific limits, the record saved will be marked 'valid' and used for deriving a currently necessary correction variable. This of course should compensate for ΔT_A, which is the present difference between the intersection point A_{mp} of the approximated lines g_1 and g_2, and the melting temperature T_{m}, i.e., the drift of the thermocouple at the fixed point. To guarantee a more reliable adjustment which is unaffected by scattering or outliers, the software superimposes filtering by means of a weighted averaging of the last valid ΔT_{A} values. If the procedure fails for

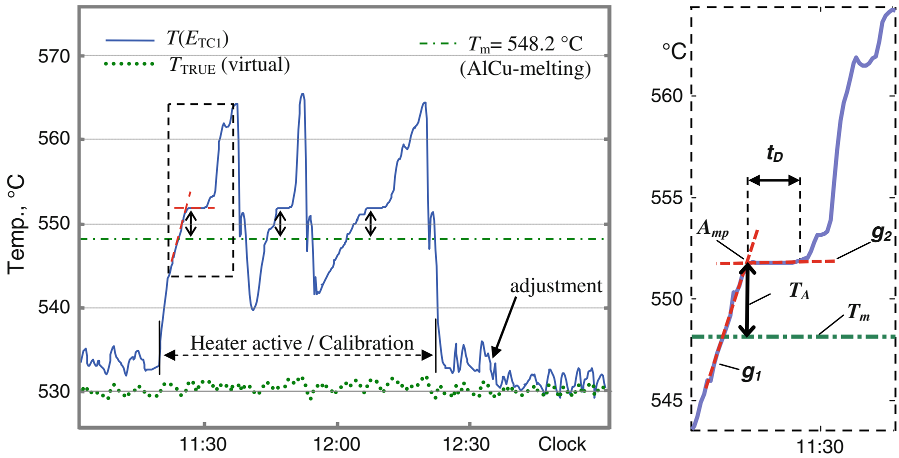

Fig. 4 Data recorded during the periodically performed self-adjustment procedure. The sensor here contains a eutectic AlCu-alloy. The detail (on the *right*) illustrates the determination of various plateau parameters, automatically calculated for each melting section. An average of the last found ΔT_A values permits a robust correction value of the thermocouple measuring circuit

any reason, a second try will be started. If it fails again, an error signal will be sent to the higher-level process control. These measures have proven successfully in practice in the last years.

Finally, the very robust offset parameter will be stored into the calibration coefficient memory of the precision transmitter and will become effective. Thus, periodically the whole thermocouple measuring circuit is adjusted for temperatures near the particular fixed point. Real series of ΔT_A data, illustrating the effectiveness of the self-adjusting procedure, are shown in Fig. 5.

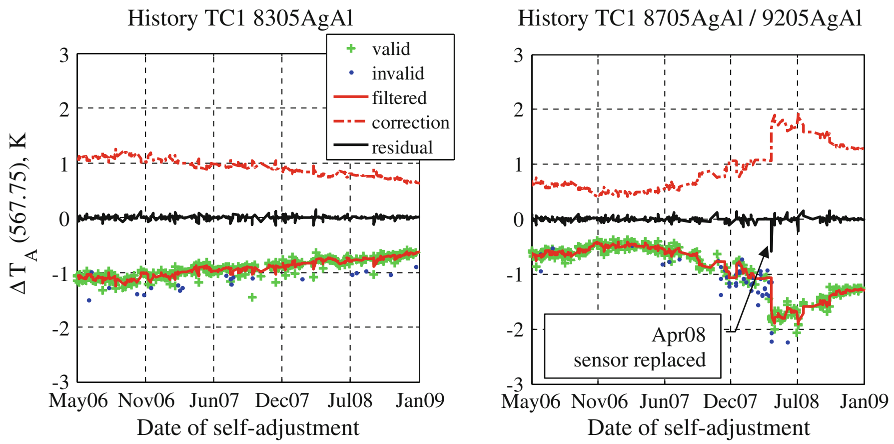

Fig. 5 Two typical history plots of the ΔT_A values and accordingly calculated corrections obtained from the consecutively performed self-adjustments during 2½ years of operation in power plant KW Heyden. Normally, the self-adjustment keeps the residuals at ±0.15 K (on the *left*). At the beginning of 2008, many successive 'invalid' data (e.g., due to leakage of metal ingot) led to a calibration error signal. After that, the sensor was replaced (on the *right*)

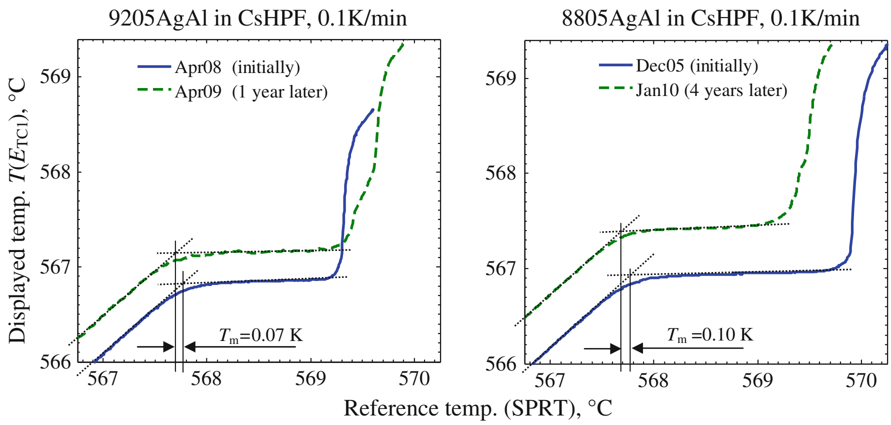

Fig. 6 Contrast of the melting plateaus of two fixed-point sensors recorded during calibrations in Cs heat-pipe furnaces before and after their long-term operation. The changes in the plateau shape characteristic for both sensors were similar—their fixed-point temperatures (determined from the reference temperature value of the intersection points) shifted insignificantly by a maximum of −0.1 K

3 Laboratory Calibration and Initial Fixed-Point Determination

Before being supplied to a power plant, each fixed-point thermocouple undergoes a basic comparison calibration ranging from 0 °C up to a temperature above the implemented fixed-point temperature. In addition, the thermocouple voltage, E_{TC1} or its temperature equivalent $T(E_{TC1})$, is recorded during very slow heating in a heat-pipe furnace passing the melting point temperature. Simultaneously, the heat-pipe temperature is recorded by a reference thermometer, as proposed in [7]. The resulting graph (see examples in Fig. 6) gives qualitative information about the purity, homogeneity, and distribution of the fixed-point metal. A flat melting plateau section indicates stable thermal equilibrium, i.e., (a) the metal ingot is of high purity, (b) in the case of alloys, it is near the eutectic or monotectic composition, and (c) it is forming a homogenous shell surrounding the central thermocouple. Then, the reference temperature value (x-axis) of the intersection of the heating-up line and the melting plateau line is a good approximation of the melting point T_m with a repeatability of about 0.03 K to 0.1 K, mainly depending on the heating rate, plateau quality, and data acquisition performance. Whether the reference thermometer is an SPRT or an Au–Pt thermocouple, the reproducibility of T_m within a good heat-pipe furnace ranges from 0.1 K to 0.3 K ($k = 2$), respectively [1,8]. Finally, both the basic calibration data and the fixed-point temperature will be stored into the sensor-related precision transmitter.

4 Long-Term Operational Experiences

4.1 Stresses Affecting the Sensor

The fixed-point thermocouples are parts of the measuring system which are most exposed to mechanical and thermal stresses during the numerous start-ups and shutdowns of the plant. Therefore, their lifetime is a determinant for the mean time to failure (MTTF) of the whole system. Another source of stress, in particular for the fixed-point sensors, is the large number of self-adjustment cycles per year (about 200) which are accompanied by the expansion and contraction of the small structured heater layer and the melting substance. In practice, a third risky situation occurs whenever the sensors have to be replaced, for instance, for preventive examinations, especially in those areas which are hot or difficult to access; unintended mechanical loads (bending, pushing), or thermal shocks may cause cracks within the ceramic parts of the sensor or may cause brittle wires to break.

4.2 Sensor Failure During Lifetime

After about 3 months (≈2 000 h), a calibration error resulted from a broken welded joint at the internal heater of a sensor in the power plant KW Altbach. The next sensor failure occurred after operation of nearly 2½ years (≈20 500 h) in KW Heyden. This was caused by the leakage of the metal ingot, which became apparent by a sudden distortion of the melting plateau shape.

Two more failures were observed after about four years (≈35 000 h) in connection with a regular inspection. In both cases, the internal wiring contact showed resistance problems. One of the sensors could be repaired, the other failed due to a breakage of fairly brittle heater wires.

Table 1 gives an overview of 15 monitored applications. Meanwhile, four sensors have been substituted for evaluating their fixed-point temperature stability (see next section). Seven sensors have shown no significant alterations in their characteristic parameters and are still operating.

So far, it has been possible to evaluate the MTTF for the sensing element of the SKTE2-measuring system to be at least 30 000 h (≈ 3½ years).

4.3 Availability

Since operation takes place in a redundant system, one of the sensors is allowed to break down temporarily. In the applications reported above, a failure of the fixed-point thermocouple is agreed to be tolerable if cleared within 2 to 4 weeks. All of the failures were fixed within 1 to 3 weeks. Therefore, a sufficiently high availability can be stated.

5 Long-Term Reproducibility of the Melting point

Whenever it seemed technologically acceptable, one of the applied fixed-point thermometers has been substituted for X-ray inspection and recalibration. Three of the failed sensors could also be recalibrated, since their main thermocouples have not been damaged and reliable melting plateaus could be generated in the laboratory furnace. So, in total, seven sensors were examined after various operation times.

Figure 6 shows in a representative way the melting plateaus of two of the identically designed AgAl fixed-point sensors. The left one was dismantled and recalibrated after

Table 1 Power plant applications of the SKTE2-system (score of Feb 2010)

Power plant (when installed)	Process location (no. of sensors)	Fixed-point material (approx. T_m, °C)	Process temperature (°C) before/after installation of SKTE2	Internal heater cycles	Sensor lifetime min–max (h)
KW Scholven (in test loop,	Live steam (2)	AgAl (567.8)	536/536	>700	3 000–32 000
10/05–07/09)	Reheated steam (1)	AlCu (548.2)	536/536	>800	32 000
KW Heyden (since 12/2005,	Live steam (4)	AgAl (567.8)	542/544	>750	35 700
still running)	Reheated steam (4)	AgAl (567.8)	542/544	>750	20 500–35 700
KW Altbach (since 08/2006,	Live steam (2)	AgAl (567.8)	540/545	>300	30 700
still running)	Reheated steam (2)	AgAl (567.8)	540/545	>300	30 700

Table 2 Comparison of fixed-point determination results obtained before and after long-term application

Sensor serial no.	Power plant	Initial calibration $T_m \pm u(T_m)$ (°C)	Instal. (date)	Remov. (date)	Operational (h/years)	Recalibration $T_m \pm u(T_m)$ (°C)	Diff. ΔT_m (K)	Remarks
7105AgAl	Scholv.	567.80 ± 0.1	04 Oct 05	18 Aug 09	33 936/3.9	567.80 ± 0.2	0.00	–
8705AgAl	Heyd.	567.82 ± 0.1	17 Dec 05	24 Apr 08	20 616/2.4	567.80 ± 0.3	−0.02	Leakage of AgAl
8805AgAl	Heyd.	567.78 ± 0.1	17 Dec 05	05 Jan 10	35 520/4.1	567.68 ± 0.1	−0.10	Broken heater wire
8905AgAl	Heyd.	567.77 ± 0.1	17 Dec 05	15 Apr 09	29 160/3.4	567.67 ± 0.2	−0.10	–
9205AgAl	Heyd.	567.77 ± 0.1	24 Apr 08	15 Apr 09	8 544/1.0	567.70 ± 0.1	−0.07	–
10806AgAl	Altb.	567.79 ± 0.1	29 Aug 06	29 Nov 07	10 968/1.3	567.77 ± 0.2	−0.02	–
10906AgAl	Altb.	567.80 ± 0.1	29 Aug 06	21 Nov 06	2 016/0.2	567.75 ± 0.1	−0.05	Broken weld joint

one year, the right one after four years of operation. In comparison to the records made during their initial calibration, the shapes of the melting plateaus differ slightly. By experience, this is generally noticeable already a few weeks after installation and may indicate partial changes in the composition or displacements within the fixed-point crucible filling. Fortunately, for the sensor designs described above, this forming-up process soon stabilizes. Moreover, also visible in Fig. 6, if there were no damages or leakages of metal ingot, we could not find significant differences between the melting plateau shapes of a one- and four-year-old fixed-point sensor. However, the most remarkable result in all seven cases of recalibration carried out so far, the approximated melting points T_m differ from initial values by a maximum of -0.1 K (Table 2). At present, this database indicates a weak negative trend of about -0.15 K at a four-year operation interval, which is the same order of magnitude as given for the calibration uncertainty of T_m.

6 Conclusions

The described fixed-point thermocouple measuring system has proved to be a highly reproducible thermometer for temperatures close to the particular melting point, even in rough industrial environments. One of the most surprising results is that no significant drifts of the melting point were found even after about four years of service life. Melting plateaus recorded in the laboratory before and after long-term operation differ by a maximum of -0.1 K. With respect to an aimed total uncertainty under application conditions of 1 K, these results are very encouraging for achieving a mean sensor lifetime of up to five years.

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