Automated calibration of temperature sensors

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Automated Calibration of Temperature Sensors

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Abstract

This paper concerns the essential problems associated with the automatic calibration of industrial thermometric sensors in the temperature range of 200°C÷1300°C carried out by means of the comparison method. The sensors to be calibrated and the reference one should be placed in a uniform and stable temperature field. It is necessary to use a dedicated furnace to generate such a field. The furnace accommodates a massive measurement insert, in the pockets of which the sensors are placed. The furnace described in this report has been built up on the basis of a 3D temperature field computer model, with a particular attention paid to the phenomenon of radiation. An individually prepared predictive control was used to reduce the setting time of the conditions required for measurements, and an algorithm was found out to automatically determine the moment of the calibration commencement. On the basis of the measurement error analysis a system of appropriate accuracy was built up for the measurement of the electric signals generated by the temperature sensors.

1. Introduction

In the result of aging the thermometric sensor characteristics change in time. For this reason they are subjected to periodic examinations, usually performed by the method of comparison.

This work concerns the essential problems associated with the design and work out of a device for the automatic calibration of industrial thermometric sensors in the temperature range of 200°C÷1300°C, carried out by means of the above mentioned method.

In order to perform the calibration, the measurement junctions of T/C's and/or the resistors of the resistive sensors to be calibrated, as well as their reference counterparts are located in a constant and uniform temperature field. In the lower temperature region up to 200°C the liquid thermostats are used for this purpose as a rule.

For the higher temperature range some special furnaces are used. They contain massive measurement inserts to equalize the temperature. The measurement junctions of T/C's and/or resistors of the resistive sensors are placed in special pockets of the measurement inserts (Fig.1).

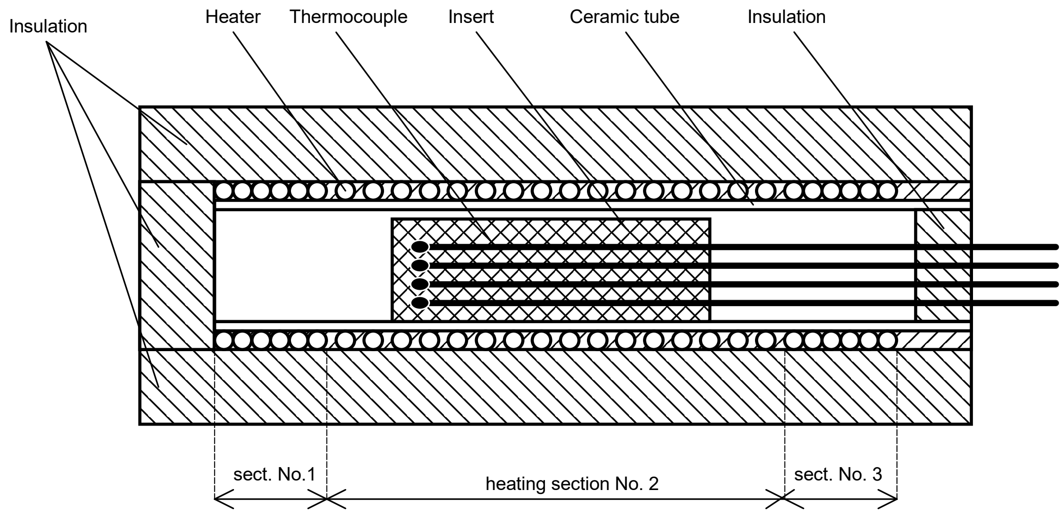

Fig.1. Furnace with insert

The calibration is usually done for several temperatures defined by the calibration procedure. That is why the measurement insert temperature control is essential to provide a uniform and stable temperature field in the insert and to assure possibly short setting time.

The procedure of automatic calibration at several pre-programmed temperatures requires an effective algorithm to detect the fulfillment of the accuracy requirements.

There is still another problem with the accurate sensor calibration, it is the measurement accuracy of the electric signals coming from the temperature sensors. The signals in question are electrical voltages that are generated in the thermocouple junctions situated in the temperature measured and in the reference temperature, or they are derived from the resistance changes of the resistive temperature sensors.

There are many manufacturers of calibrators intended for the calibration of industrial temperature sensors, but the available information concerning accuracy is usually scanty.

This paper analyses the sources of errors that crop up during the calibration of industrial temperature sensors by means of furnaces, and possible ways of the error reduction down to an acceptable level.

2. Conditions of calibration measurements

The best uniformity of the measurement insert temperature field is required for the Pt100 sensors of Class A, and those of Pt-PtRh10% (S Type) Class 1.

Fig.2 shows the plot of maximal error for those sensors defined by the international standards.

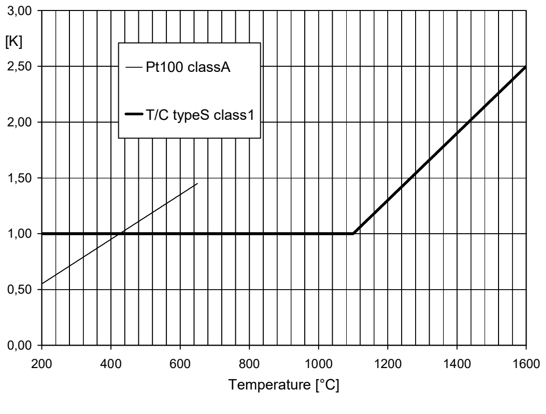

Fig.2. Calibration error limits for the sensors of Pt100 Class A and Pt-PtRh10% (S Type) Class 1

The calibration device should allow for the calibration of both mentioned sensors; in other words it should meet the requirements for each of the two sensors simultaneously.

In the range of 200°C÷425°C the requirements for Pt100 prevail, but for the higher temperatures the requirements of the Type S thermocouple are getting upper hand. For the range of 425°C÷1000°C the temperature distribution over the measurement insert should have the uniformity better than ±1K, while it may be slightly worse above, and the requirements become more stringent below 425°C.

For the calibration of standard thermocouples in the temperature range of 200°C÷1300°C the requirements for the temperature field surrounding the sensor junctions can be defined as follows:

- The deviations of the insert temperature mean value can not differ by more than 10K from the nominal calibration temperature.
- The temperature differences between the reference junction and those of the calibrated thermocouple junctions usually should not exceed ±0.2K (but for 200°C they should be less than ±0.1K).
- The temperature gradient along a sensor should not exceed 0.5K/cm along a distance of at least 5 cm
- The temperature mean value stability should be better than 0.05K during the calibration measurements.

The above conditions should be kept in the quasi-stationary state. An appropriate thermal system arrangement ought to be used to meet such requirements, and moreover, the control system should be equipped with some algorithms that would allow to detect the fulfillment of the requirements.

The Pt-PtRh10% (S Type) sensor has the lowest sensitivity, which is about 10μV/K, and the required accuracy of measurement for the Class 1 at 1000°C is ±1K (Fig. 2). So it follows, that the measurement accuracy of the measured voltages, measured differentially, should not be worse than 0.01% of measured values ±1μV (ignoring possible small DC offset, which has no effect with differential voltages, as it is cancelled during subtraction).

3. Arrangement of the furnace

The requirements formed in Chapter 2 can be fulfilled by a horizontal tubular furnace with a metal measurement insert of the layout shown in Fig.1.

Before the technical design, an extensive modeling of temperature distribution in the furnace was done, with a particular attention paid to the temperature distribution in the measurement insert. Regarding wide range of working temperature, during modeling we took into account three forms of heat exchange inside the furnace: conduction, convection and radiation. The share of radiation in the process is much varying, as its intensity depends on the fourth power of the absolute temperature. In order to determine the heat exchange by radiation it is necessary to find the angle dependant coefficients for each combination of all discrete surfaces inside the furnace chamber containing the insert. The insert itself not only obstructs the radiation heat exchange by shielding, but also by its eccentric location deforms the temperature field in the insert.

There is a wide choice of professional software available, intended for the temperature distribution calculations, as for example QUICKFIELD, FLUX, NISA, OPERA or PROFI. Taking into consideration a possibility of calculations of the radiation heat exchange with regard to multiple reflections, we have chosen the NISA program of Engineering Mechanics Research Corporation from USA [1] that employs the finite element method. We verified the results of calculation with those derived from the measurements of physical models built up on the basis of modeling [2,3]. Fig.3 shows an example of a temperature field calculated for the designed furnace.

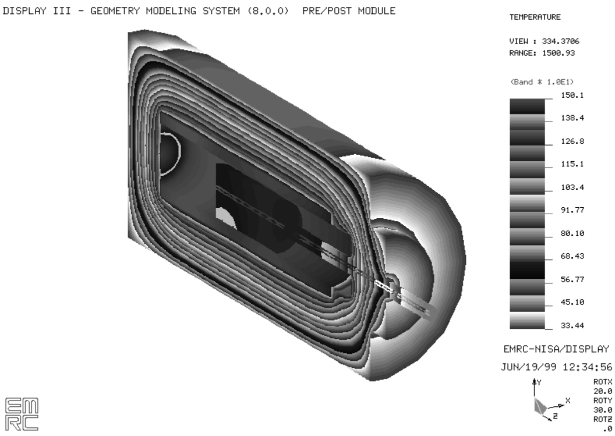

Fig. 3. Distribution of the temperature field inside the furnace with the insert

As a result of modeling and the examination of physical models we designed a horizontal tubular furnace containing a measurement insert that met the pertinent requirements. The furnace affords a simultaneous calibration of 5 thermometric sensors in the temperature ranging from 200°C to 1300°C.

To shape an appropriate static temperature field in the measurement insert for a wide temperature range, the furnace was equipped with a 90 mm diameter heater divided into 3 sections with the heating power concentration varying along the reactor axis (Fig.1).

The middle section and section no. 1 are connected electrically in series and have common supply and their temperature is controlled by a single control loop (Fig.5). The border section no.3, on the side where the sensors are loaded into the furnace, has a separate supply and is controlled by another control loop. Such an arrangement allows to compensate for the thermal losses associated with inconstant thermal isolation of the furnace entrance that depends on several factors, and particularly on the number and the thickness of the calibrated sensors.

Fig.4 shows the achieved temperature difference between the uppermost and the lowest pocket for the measurement insert of Khantal A1 at 1000°C versus the distance from the respective pocket's bottom. The reference sensor is placed in the middle pocket.

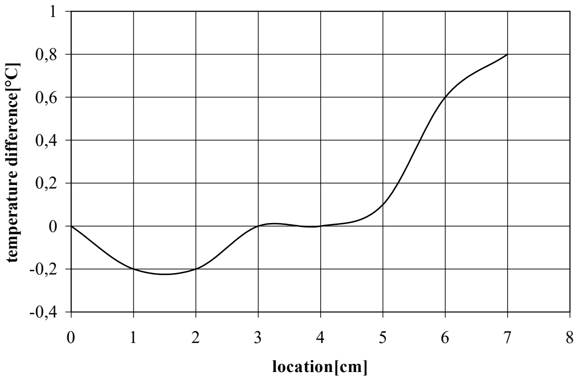

Fig. 4. Temperature difference between the top and the bottom pocket of the insert

We want to emphasize that because of high temperature (up to 1300°C) Khantal A1 was used in the described calibrator, despite that its thermal conductivity is much worse than that of nickel used up to 1000°C or brass, whose use is limited to 600°C. Higher thermal conductivity affords better temperature uniformity. For the highest temperatures ceramic measurement inserts can be used.

4. The process control and temperature regulation

The process of automatic calibration needs stable temperature to be kept at several pre-programmed levels, according to the requirements presented in Chapter 2. We achieved that in our system with a supervisory PC (Fig.5). The computer is coupled with a multichannel temperature measuring system and with a heater controller by means of a serial galvanically insulated interface. The computer receives data from the reference sensor and from the sensors to be calibrated and it calculates the driving signals for the temperature controller. In the result the required values of temperature are obtained in the measurement insert for the consecutive levels of calibration.

The decision on the calibration measurement commencement is taken automatically on the basis of the analysis of the following data: the temperature mean value, momentary time derivative of the temperature, and the trend of temperature variation estimated for a longer time [6].

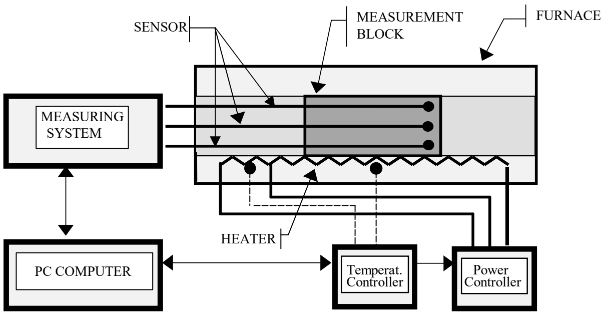

Fig. 5. The scheme of calibrating system

By control of the heater temperature only, the temperature setting with appropriate accuracy took about an hour for each temperature point, so there was a need for increasing the system throughput by speeding up the thermal transient process for each calibration point.

The control used is based upon a model of furnace with a measurement insert, which was described as a MIMO system with equivalent delays [4]. One of the tools used for its analysis was space digitization and linearization in the proximity to the working point. Considering that the transfer matrix of the controlled process is singular, the optimal control was found by means of dynamic programming. The resultant optimal controller is of a very high order and makes use of previous values of the control vector and the previous values of the measurable state variables that represent the unmeasurable internal state variables. Such a controller is much difficult to implement, particularly on the account of high parameter variations with temperature. That is why a suboptimal control of reduced order and based only on the observable state variables was used instead of the optimal. We used a direct synthesis method of our own to reduce the optimal controller to its suboptimal form [5,6,7].

The suboptimal predictive controller was implemented as a cascade controller of variable structure that comprises, among the others, the control loops of the heater sections described in the chapter concerning the furnace arrangement. The supervisory control loop is closed through the temperature measuring system, the supervising computer and the heater temperature controller. On the basis of thermal state analysis the supervising computer selects the appropriate controller structure. Fig.6 shows an example of temperature change in the central heater section and the temperature in the reference sensor placed in the middle pocket of the measurement insert.

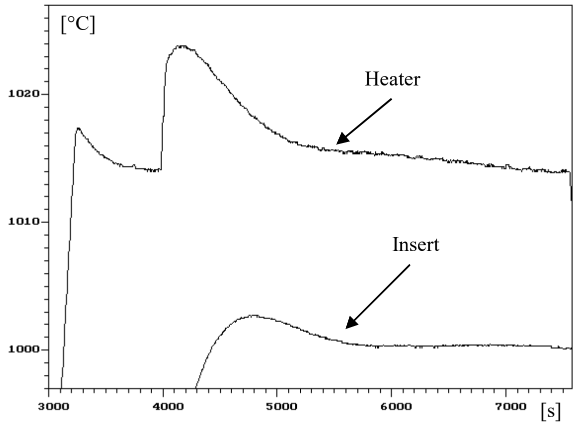

Fig. 6. Temperature of the heater and insert during stabilization

The described predictive control yielded the temperature stabilization exactly at the required level and it also reduced the temperature setting time for various temperature levels to the range of 1/2 to 1/3 of the original value.

5. Measuring the sensor electrical signals

The sensor thermal sensitivity is an essential factor that must be taken into account during designing the system processing the electric signals from the sensors. As it was mentioned before, the lowest sensitivity has the Pt-PtRh10% (S type) sensor. Its value is of 10μV/K, and the accuracy required at the level of 1000°C is ±1K for the Class 1 (see Fig. 2). As it was discussed earlier, the final voltage measurement accuracy should be not worse than 0.01% of the actual value ±1μV. For the resistance measurement the accuracy of at least 0.01% of the measured value should be maintained.

Having analyzed all potential measurement error sources we designed a dedicated multichannel measuring system. In the implementation we used amplifiers with galvanically insulated input and containing autozero functions, an 18–bit integrating A/D converter (MAX–132) and the 8032 controlling microprocessor.

To reduce the measurement noise and to obtain the desired resolution we used digital data processing. The supervising microprocessor performs the following functions:

- drives the autozero switches of the input amplifiers,
- controls the switching of gain in the input amplifiers,

- provides the timing signals for the A/D converter,
- computes the temperature with regard to the characteristics of the sensors used,
- controls the communication with supervisory computer

6. Summary

The paper discusses the basic problems concerning the design of a system for the calibration of industrial thermometric sensors. They include:

- Design of a tubular furnace with a multisection heater creating a uniform temperature field, based on a 3–dimensional computer model; in which a particular attention was paid to the phenomenon of radiation inside the furnace chamber.
- Work out of a measurement insert temperature predictive control, in the result of which we obtained a precise temperature control within the measurement insert and much reduced setting time for the necessary conditions of the calibration measurements.
- Finding an algorithm for the automatic detection of fulfillment of the accuracy requirements for the measurement commencement.
- Analysis of the measurement error sources and the work out of an accurate multichannel measurement system with insulated channels for the measurements of temperature sensor signals.

The described work resulted in a complete system that fulfils all the requirements defined at the beginning of this paper.

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