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Numerical approach to the evaluation of calibration uncertainty of contact temperature sensors

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Summary

The work presents a numerical approach for the evaluation of uncertainty in calibration systems for contact temperature sensors. This type of measurement is widely used in practice, but its results are influenced by systematic errors due to the interaction between sensor and measured surface. The uncertainty of the system is evaluated through the numerical simulation of its temperature field, when the sensor to be calibrated is placed on the reference body's surface. The procedure is validated on the basis of a simulation carried out for two calibration systems, for which the experimental data are available in literature.

Introduction

Contact surface temperature sensors are widely used in scientific and industrial applications because are simple to use and their measurement is independent from the emissivity of the surface. These sensors are particularly suitable for industrial processes where it is necessary to measure time dependent surface temperatures . The metrological traceability of contact temperature sensors is quite different in Europe. In fact, some countries have developed surface temperature standards in the range 10÷300 °C (France) or up to 500 °C (Germany). Other countries, for instance Italy, still use radiation thermometer as standard to measure surface temperature and a thermostatic liquid bath with a standard resistance thermometer to calibrate the contact surface sensors. Obviously, calibration conditions are quite different from real ones and, therefore, many influence parameters, related to the thermal coupling between surface and sensor (shape of the sensor, surface properties, contact thermal resistance, etc.) and the thermal exchange with the surrounding environment (air temperature, air speed, etc.) should be taken into account in the calibration process.

Errors sources can be generally summarized in two different types: systematic and random. Systematic errors, studied in this work, are related to a known physical reason, and have almost the same value and sign at each measurement, and for this reason they can be corrected using an appropriate algorithm. Obviously, even if the error can be corrected, the uncertainty related to this correction will not be negligible and will have to be considered in the uncertainty propagation law. However, the experimental evaluation of these errors is not quite simple [1-4] and for this reason, several mathematical models,

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based on simplified assumptions [5-10], have been proposed. In most cases, especially for calibration systems, these models cannot fully explain the phenomena involved.

This work presents a numerical procedure, based on the finite element method [11], for the calculation of the systematic errors due to the interaction between the sensor and the measured surface. Despite the developments of numerical methods, only recently the measurement science has started to think about using these methods [12]. The proposed procedure, once adequately validated, will be used for the design of a calibrating system for contact temperature sensors.

Systematic errors in contact temperature measurements

Systematic errors in contact temperature measurement can be described according to the available literature [13] as follows: i) undisturbed value T_0: temperature of the reference surface when no sensor is placed on it, and the surface only interacts with the surrounding environment; ii) available value T_S: temperature of the portion of the reference surface where the sensor is placed; iii) realised value T_R: temperature deduced from the electrical signal received by the sensor.

Obviously, the calculation of the undisturbed value of the reference temperature T_0 cannot be separated from the uncertainty of the sensors used for its measurement. These can be pyrometers, to directly measure the reference surface temperature, or two or more sensors placed in the reference body, from which the temperature of the reference surface is extrapolated. In the latter case, the temperature profile distortion due to the sensor placement on the reference surface, may cause a further error (T_E in Fig. 1.b), that is not considered in this work, but will be studied in the future. The interaction between the reference surface and the sensor is sketched in Fig. 1.a. The figure shows the fin effect due to the sensor, and the related distortion of the temperature profile in the solid near the measuring section.

Fig. 1.b shows the qualitative temperature profile along the sensor axis, in the case of undisturbed temperature (green line) and disturbed field (blu line). Furthermore, the red temperature profile represents the effect of the extrapolation of the surface temperature from two points when the temperature field is disturbed by the sensor. The difference $\Delta\theta$ between the undisturbed temperature T_0 and the realised value T_R, not considering the calibration error just mentioned (T_E-T_0), can be considered as the sum of three contributions:

$$\Delta\theta = T_R - T_0 = \Delta\theta_1 + \Delta\theta_2 + \Delta\theta_3 \tag{1}$$

where $\Delta\theta_1 = T_S - T_0$, is known as the *first partial error*, and is caused by the deformation of the temperature field due to the sensor; $\Delta\theta_2 = T_{SEN} - T_S$, known as the *second partial error*, is the difference from the available value caused by the contact resistance between the reference surface and the sensor; and $\Delta\theta_3 = T_R - T_{SEN}$, *third partial error*, is due to the fact

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that the sensible element (a resistance or a two-metal junction) in the sensor is placed at a certain distance from the reference surface.

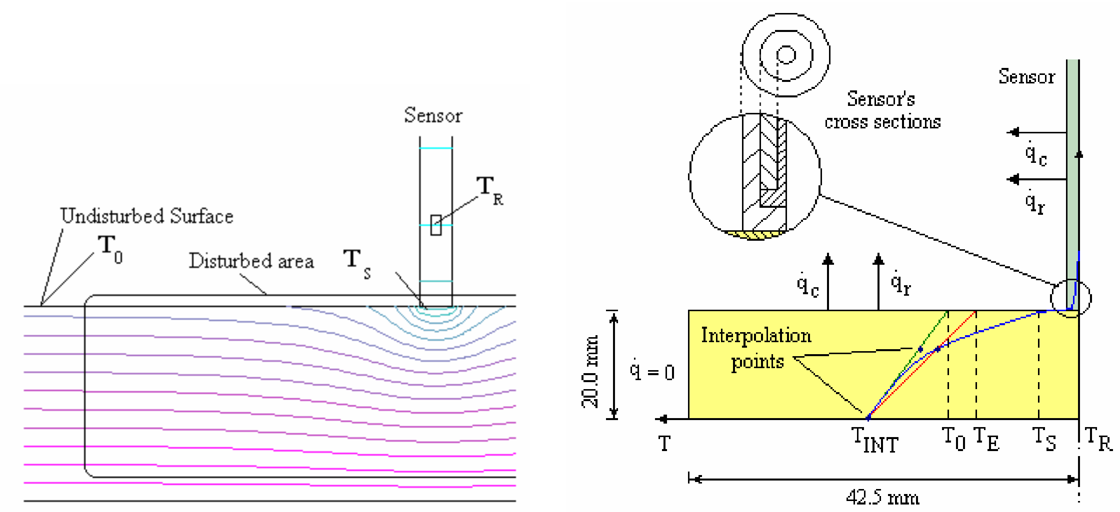

Fig1. Sketch of temperature distribution in the calibration system with the sensor: (a) isotherms, (b) Computational domain and temperature along the sensors axis.

Numerical model

The theoretical models developed to study contact temperature errors are generally based on simplified assumptions. In same cases this has led to approximate conclusions, like for instance to believe that, in order to reduce the first partial error, it is necessary to decrease "the heat conducted from the measuring point along the sensor" [9]. However, if the sensor is perfectly isolated, the temperature field would be distorted in the same way, but with an opposite value. The only way to reduce this error would be to design the sensor and its coupling with the surface, so that the sensor's thermal behaviour will be the same as that of the environment.In this paper, a numerical procedure for the determination of the first and third systematic (partial) errors in contact temperature calibration systems is proposed. The procedure is based on i) the use of the Finite Element Method (FEM) for the evaluation of the temperature field in both, the system and the sensor, and ii) the calculation of the error due to the presence of sensor. The numerical procedure is validated by simulating two calibration systems, realised by different metrological institutes, the French Laboratiore National d'Essais (BNM) and the Hungarian National Office of Measures (OMH), for which the results are available in literature [3].

The system studied, sketched in Fig. 1.b, with the boundary conditions used for the numerical model, is a cylinder of 85mm of diameter and 20 mm of height, which is kept at the temperature desired by heating from the bottom base. The cylinder has a lateral

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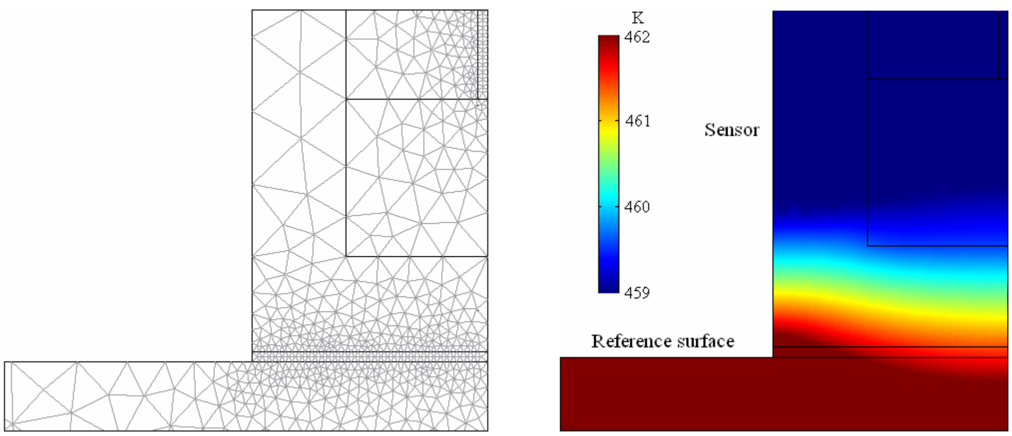
guard ring and it exchanges heat with the environment (23 °C) from the upper base. In order to reproduce these conditions, the axi-symmetry of the cylinder has been considered, and therefore a bi-dimensional domain was studied; the lateral surface of the cylinder was assumed to be adiabatic, and the bottom base of the cylinder was considered to be at constant temperature, the one that allows the upper base to have the desired temperature. This type of boundary conditions had to be assumed because not enough information was available from the literature about the heating system. The upper surface of the cylinder, as well as the surface of the sensor, exchange by convection and radiation with the surrounding environment. In order to simulate the radiation, configuration factors have been calculated for the surfaces involved, and the environment has been considered as a black body at 23°C. The convection coefficients between the surfaces and the air were calculated on the basis of the relations available in literature [14].



(a) (b)

Fig. 2. Numerical solution near the measuring section for one of the problems considered: (a) computational grid; (b) isotherms.

The sensor's geometry has been approximated with an equivalent axi-symmetrical, composed of a spire covered with a metallic material, equivalent to the actual sensor from the point of view of the heat transferred to the environment. This approximation has been already used in literature [6] and is not further explained here.

Results

The results obtained are presented in Figg. 2 and 3. In particular, Fig. 2 shows an example of the mesh used for the calculation (Fig. 2a) and the temperature field (Fig. 2b) around the measurement section, for one of the cases considered. The mesh is automatically adapted on the basis of the local aposteriori error estimate of the solution.

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The grid is seen to be refined where the highest temperature gradients are. From Fig.2.b it is clear the distortion of the temperature profiles near the measuring section, and their concentration near this section, which is related to the heat transferred through the sensor.

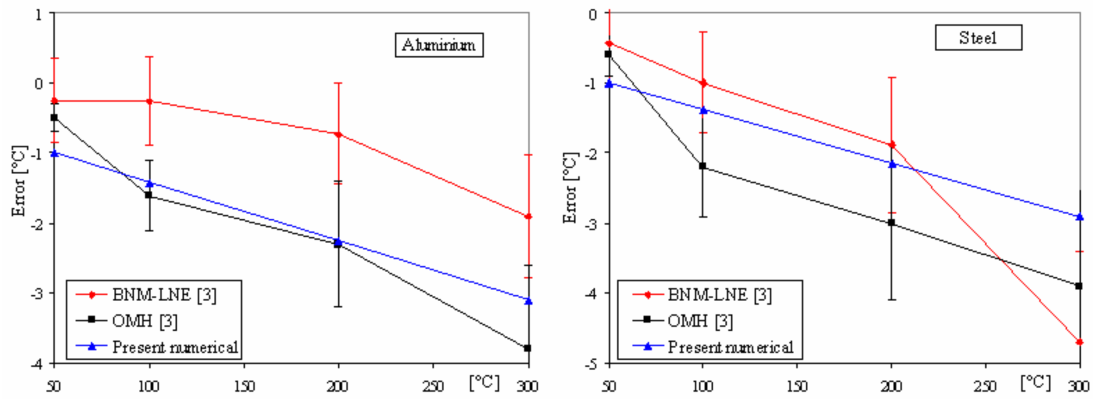

Fig. 3. Comparison of numerical and experimental results of the errors of the calibration system studied.

Fig.3 shows a comparison of the error in the temperature measurement, evaluated experimentally [3] and numerically in this work. It is clear from this figure that when the material used for the reference body is aluminium, the numerical data and the OHM results are not compatible with the BNM values. Because of the lack of further data about the two experimental apparatus in literature, it is not possible to correctly explain these differences. Nevertheless, when the material used for the reference body is steel, the errors calculated numerically are always compatible with the experimental data both for BNM and OHM values.

Conclusions

The work presents a numerical procedure for the calculation of first and third (partial) systematic errors in contact temperature measurements. The procedure, based on the numerical solution of the temperature field in the reference body and the sensor, is validated by simulating two calibration systems, whose results are available in literature. The comparison has shown that the procedure can accurately predict the systematic error, as the results obtained proved to be compatible with the experimental results. The procedure will be used in the near future for the design of new calibration systems for temperature contact measurements.

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