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DETERMINATION OF HEAT RESISTANCES BETWEEN INSTALLED THERMOCOUPLE AND BODY USED FOR COMPUTING HEAT TRANSFER COEFFICIENTS

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Abstract: *To determine heat transfer coefficients on a surface, an inverse task is used that requires either measured surface temperature history or, more often, measured temperature history inside the body. To measure temperature inside the body, a thermocouple must be placed inside. The installed thermocouple disturbs the homogeneity of the temperature profile and thus the measured temperature is different from the original one. This paper describes an experiment and a computational method for determination of heat resistances between the thermocouple and the body. Comparison of computed heat transfer coefficients for the fixed model and for a model that ignores installed thermocouple is made.*

Key Words: heat transfer, sensor, calibration, experiment, temperature measurement

1. Introduction

Many different numerical approaches [1] for solving heat conduction in a solid body are already known. Almost all are in a very good agreement with both the reality and analytical solution. However, unknown material properties and boundary conditions, which are necessary for solving heat conduction in a solid body, cause problems. This is because of the variety of used materials and boundary conditions. Usually, precise parameters are not available for the problem under the solution. This paper describes an alternative way to calibrate sensors that are used for measuring boundary conditions. The designed sensors are used for measuring heat transfer coefficients (HTC) in applications like continuous casting, descaling, and rolling technology.

In most cases, the heat transfer phenomenon is usually measured indirectly. For this purpose, thermocouples are placed inside the body that is under investigation. An inverse task has to be used to compute HTC from the measured temperature history.

An inverse task, which computes HTC, is one of many ill-posed problems [2]. This means that a small error in the input data results in a big error in the output data. Errors in the input data in computations are of three different kinds:

- Geometry and dimensions of the computational model

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- Material properties of materials used
- Noise in measured temperature histories

This paper describes how to calibrate the computational model using an additional experiment with the sensors used and shows the influence on the results computed from the real measurement.

Nomenclature:

C .... criterion function, K

c_p .... specific heat, J/kg.K

h .... heat transfer coefficient, W/m^2.K

i .... time step index

k .... thermal conductivity, W/m·K

k_u .... thermal conductivity of the material in the upper part of the gap, W/m·K

k_l .... thermal conductivity of the material in the upper lower of the gap, W/m·K

n .... number of time steps

T .... temperature, K

T^* .... computed temperature, K

t .... time, s

x, z .... spatial coordinates, m

ρ .... mass density, kg/m^3

2. Sensor description

To measure temperature inside the body, special sensors with built-in K-thermocouples are used as shown in Figure 1. The main body of the sensor is made of stainless austenitic steel. A hole of 1.1 mm in diameter for a thermocouple is made from the side of the sensor. The axis of the hole is 1 mm under the investigated surface and is perpendicular to the expected heat flux, so that the most important part of the inserted thermocouple lies in one isotherm. Inside the sensor, a shielded ungrounded K-thermocouple is placed. The gap between the sensor and the thermocouple is filled with copper or ceramic material that can be exposed to a higher temperature than copper.

Sensors of this type are used mainly for descaling experiments but very similar sensors are used for measuring temperature during the rolling process. During measurements that serve for computing HTC, the sensors are placed in the steel object on which the HTC is investigated (see Figure 1).

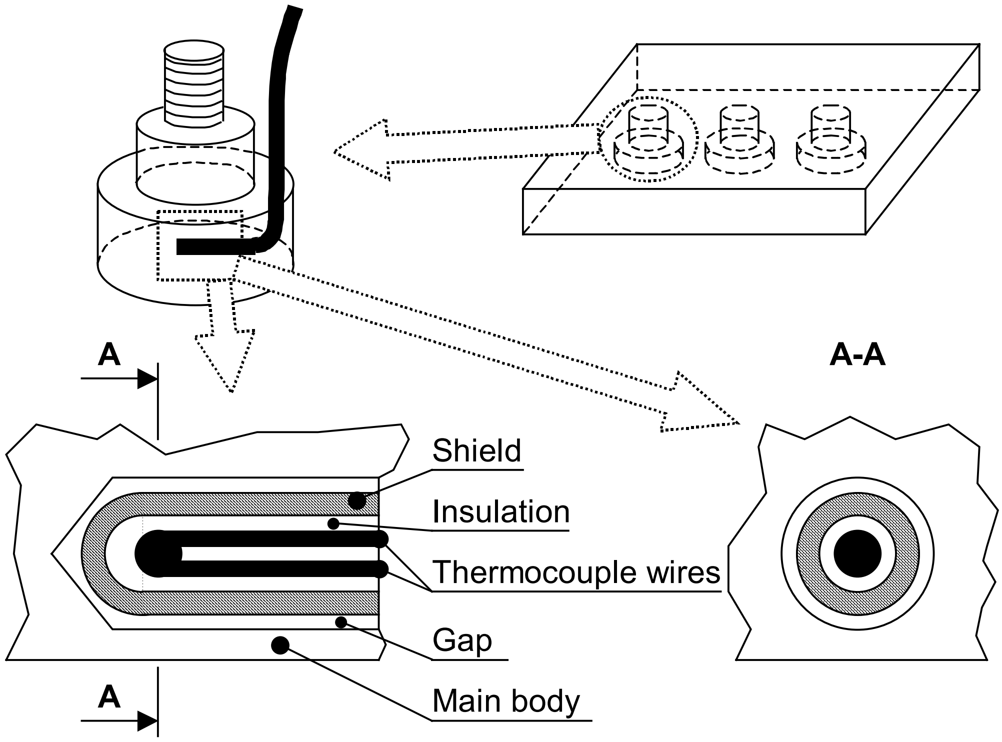

Figure 1 - Application of sensor, and its detailed structure

3. Calibration Experiment

None sensors are exactly the same. The positions of the junction point inside the shielded thermocouple differ. Also the hole inside the sensor is a bit bigger than the thermocouple so that its position can differ. As the thickness of the material in the gap differs, the heat-resistance does too. These are the main reasons why the calibration experiment has to be done for each sensor.

The main idea is to perform an experiment we know all about except the heat resistance between the sensor and built-in thermocouple. The sensor at room temperature is exposed to a high temperature. The measured temperature history must match the computed history in case the computational model is correct.

The experimental apparatus (see Figure 2) consists of an arm with an attached sensor that can be slid down and up. The temperature is measured using four thermocouples during the calibration process. One thermocouple is in the sensor, two are inside the copper rod, and the last one measures temperature inside the high-conductive grease.

At the beginning of the experiment the copper rod is heated up to a uniform temperature and the sensor is held at room temperature. A high-conductive grease is applied onto the surface of the copper rod to ensure a full contact between the sensor and copper rod. Afterwards, the sensor is stuck to the heated copper rod and the switch indicates the time when the contact occurred. A 0.05 mm thin pad placed in the grease ensures every time the same thickness of the grease between the sensor and the heated copper rod.

The recorded temperature histories are shown in Figure 3. The rapid decrease in temperature inside the grease indicates the time when the sensor was stuck to the heated copper rod.

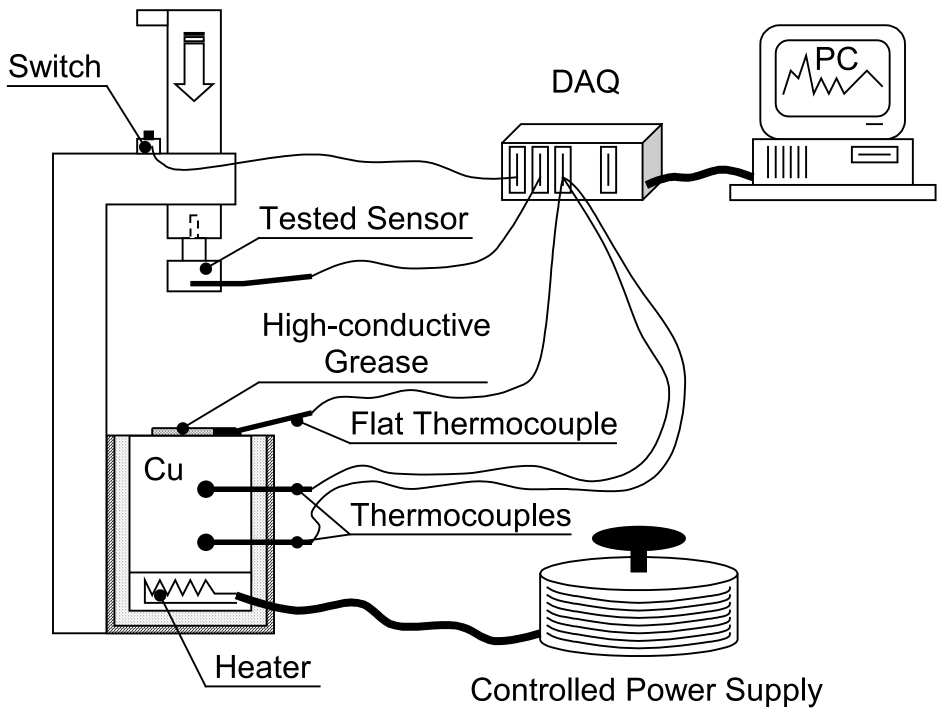

Figure 2 - Experimental apparatus for sensor calibration

4. Computational Model

A 2D axis-symmetric model was used as shown in Figure 4. The model consists of the heated copper rod, high-conductive grease, and the tested sensor. The model includes the shielded thermocouple with all its parts. The thermocouple must be taken into account because the homogeneity of material is disturbed by the inserted thermocouple, and thus the temperature profile is also disturbed.

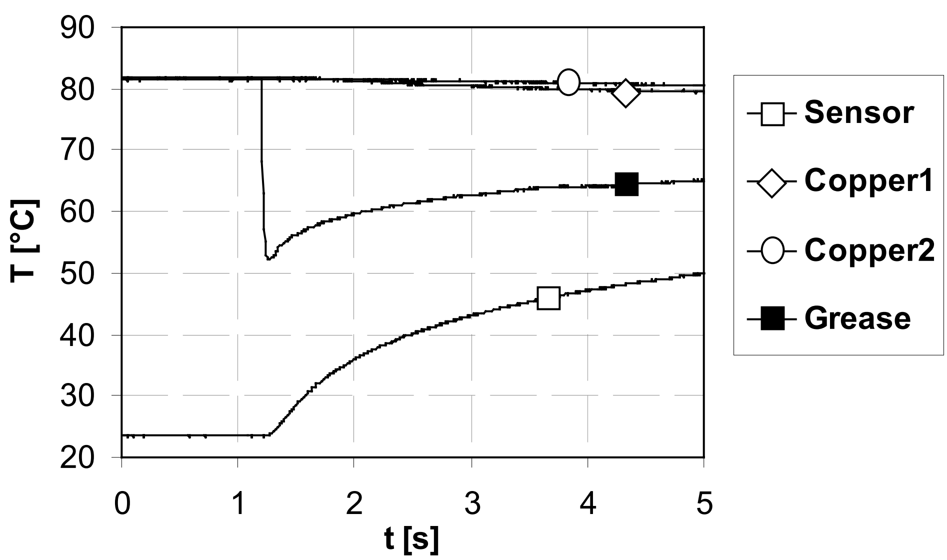

Figure 3 - Measured temperature histories

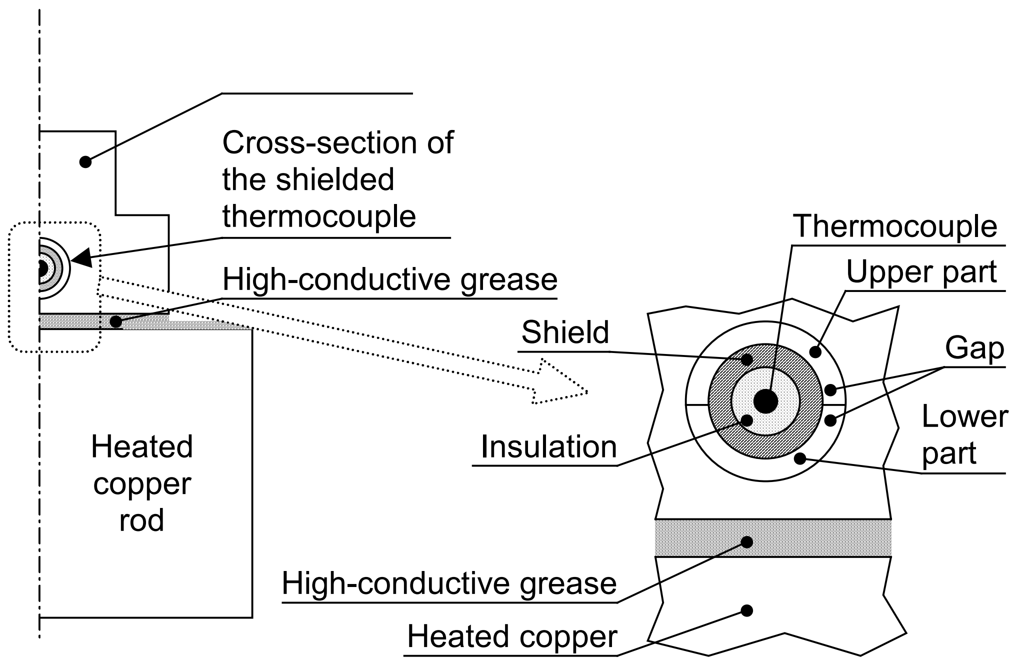

Figure 4 - Computational 2D model

An example of the temperature field around the thermocouple is shown in Figure 5. This 3D chart shows a part of the computed temperature field of the 2D computational model around the thermocouple 1 s after the beginning of the experiment. A quite flat circular part represents the cross-section of the thermocouple. A very steep change in temperature represents the high conductive grease between the colder sensor and heated copper. In this case the gap is supposed to be filled with copper that has an extremely high conductivity. This high conductivity causes "almost" constant temperature within the copper annular ring because the high conductive copper averages the surrounding temperature.

This 2D model and the general unsteady heat conduction equation

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)=\rho c_p\frac{\partial T}{\partial t} \tag{1}$$

are used for computing the temperature profile and temperature history [3]. The Control Volume method is used for solving Eq. (1) as described in [4]. This 2D model is fully insulated on the surface. Thereby heat conduction occurs only inside the model from the heated copper to the colder sensor.

5. Model Calibration

The 2D computational model described in the previous section is modified to match the computed temperature histories with the measured ones. Supposing the axis of the hole of 1.1 mm in diameter is precisely 1 mm under the investigated surface, the following parameters can vary:

- Junction point inside the shielded ungrounded K-thermocouple
- Position of the thermocouple inside the hole of 1.1 mm in diameter, and the thickness of the material in the gap between the sensor and the thermocouple

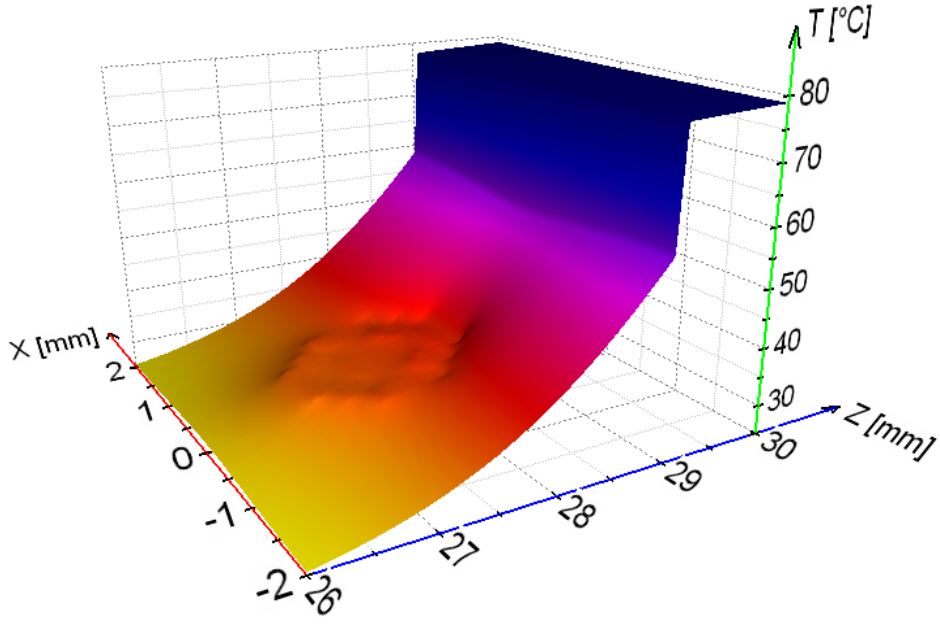

Figure 5 - Disturbed temperature profile in place where the thermocouple is positioned

- Material properties (thermal conductivity, specific heat, and mass density) of the material that fills the gap

Computational experiments showed that knowing the specific heat and mass density of the material that fills the gap, the remaining parameters can be estimated by only two parameters – thermal conductivity of the material that fills the gap in the upper and lower parts. The dimensions of the model remain, only the material that fills the gap is divided into the upper and lower part. Both parts can differ in thermal conductivity. Changing the thermal conductivity independently allows compensation of the position error of both the junction point and thermocouple inside the hole. The Downhill Simplex optimization method [5] is used for finding the appropriate thermal conductivity of the material that fills the gap in the upper and lower parts.

5.1. Downhill Simplex optimization method

Optimization methods usually search for a minimum of some function. There are two types of minimums - local and global ones. The function has one (one-dimensional) parameter or more parameters (multi-dimensional) that are optimized. These parameters can be either constrained or unconstrained.

The Downhill Simplex requires no derivative information and is therefore useful for optimizing problems computed using numerical methods or methods where no analytical description is known. The optimized space is searched using a moving simplex. A simplex is the geometrical figure consisting, in n dimensions, of n+1 points (or vertices) and all their interconnecting line segments, polygonal faces, etc. The algorithm is supposed to make its own way downhill through the unimaginable complexity of N-dimensional topography, until it encounters a minimum. As the simplex moves it adaptively changes its size. Figure 6 illustrates possible changes in the simplex size within one step and simplex movement during three steps for a 2D problem. The simplex was expanded during the first step. The mirrored simplex (dotted

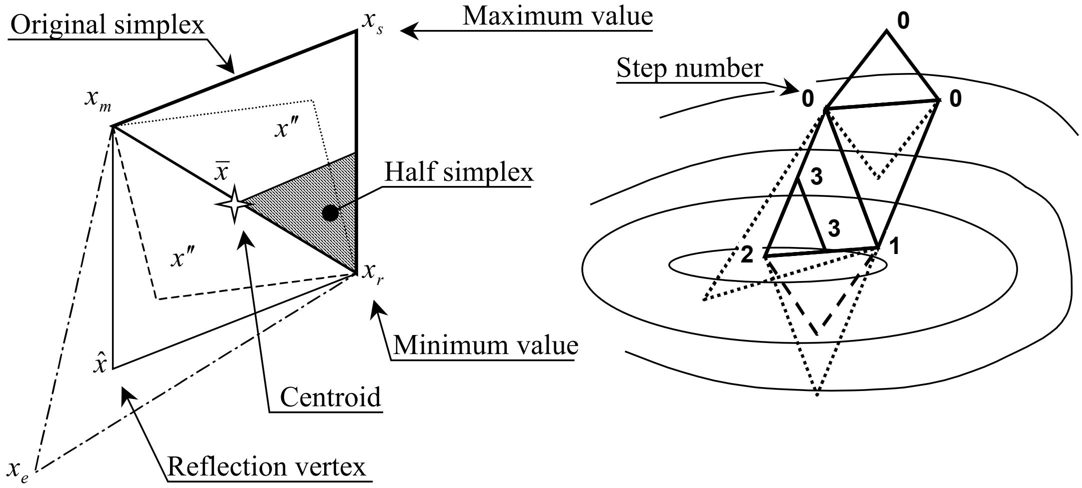

Figure 6 - Vertex meaning within one step and moving simplex in 2D space.

line) was thrown out. During the second step, the expanded simplex was thrown out and the mirrored one was accepted. During the third step, neither the mirrored simplex nor the contracted one (dashed line) was accepted. Therefore, the half simplex was used.

5.2. Thermal Conductivity Optimization

To calibrate the computational model, two parameters are optimized - thermal conductivity of the material in the upper and lower parts of the gap, k_u and k_l, respectively. If the computational model matches the real sensor, the computed temperature history must match the measured one. Therefore, the criterion function C for the optimization method is used as follows

$$C(k_u, k_l) = \sum_{i=1}^{n} \left(T_i^* - T_i\right)^2 , \tag{2}$$

where T and T^* is the measured and computed temperature of the thermocouple inside the sensor, respectively.

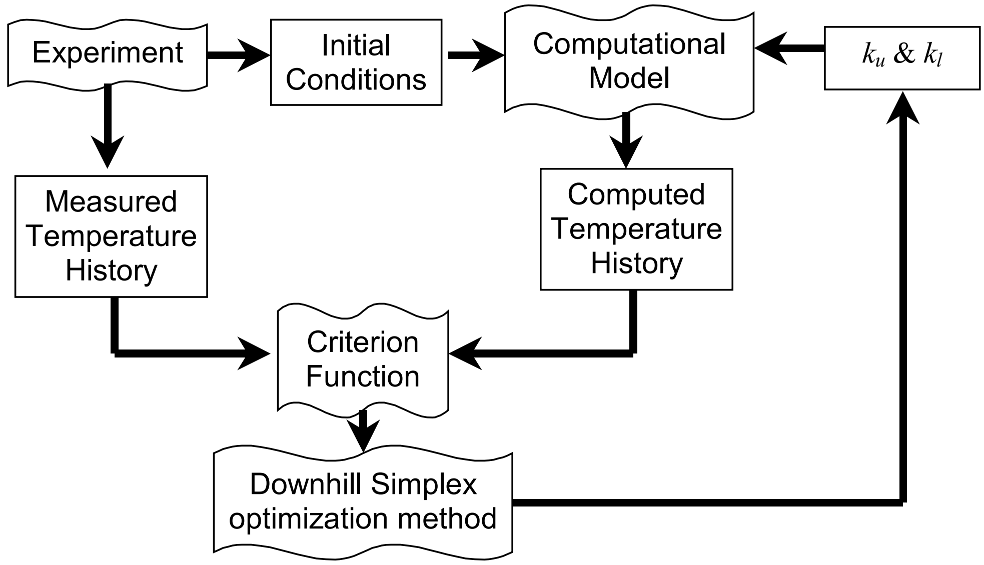

Figure 7 – Data flow during the optimisation process

First, an experiment is performed to obtain initial conditions and the measured temperature history inside the sensor. Only the initial conditions are used for the computational model. Using the initial conditions and the computational model, the temperature history is computed. The computational model can differ in thermal conductivity of the material in the upper and lower parts of the gap. The computed and measured temperature histories are used in the criterion function. The minimum of this function is found using Downhill Simplex optimization method (see Figure 7). For each step (different k_u and k_l) in this method, a new temperature history is computed. The minimum of the criterion function represents the best k_u and k_l values.

6. Results

First, three experiments were made to ensure that the thermal parameters of the high conductive grease are correct. The gap between the sensor and thermocouple was filled with grease. Three experiments, which differ in the thickness of the grease between the sensor and heated copper, were made using this sensor. The measured temperature histories and the ones computed using the calibrated model are almost identical (see Figure 8). The calibrated computational model differs only in the thickness of the grease between the sensor and heated copper. Perfectly overlapping computed and measured temperature histories have confirmed the correctness of the thermal parameters of the high conductive grease.

Another experiment was made to show the importance of usage of the calibrated model. For this experiment, a sensor where the gap was filled with ceramic material was used. The measured temperature history inside the sensor (*T measured*) and the computed temperature history with the calibrated model (*T therm.*) are shown in Figure 9. Both curves are almost identical. Even more, this figure shows the computed temperature history for the model with no internal structure - homogeneous steel (*T steel*). It is

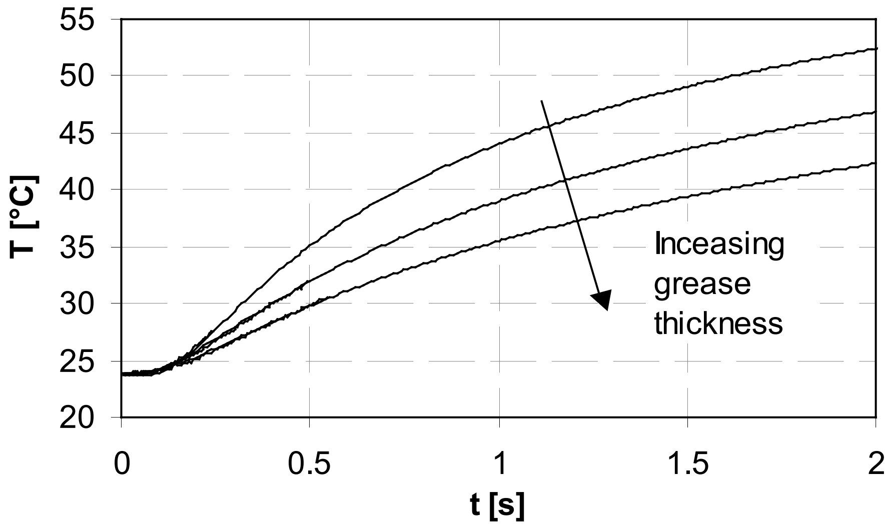

Figure 8 - Perfectly overlapping measured and computed temperature histories for three different thicknesses of the high-conductive grease and the same computational model of the sensor (0.05 mm, 0.11 mm, and 0.17 mm)

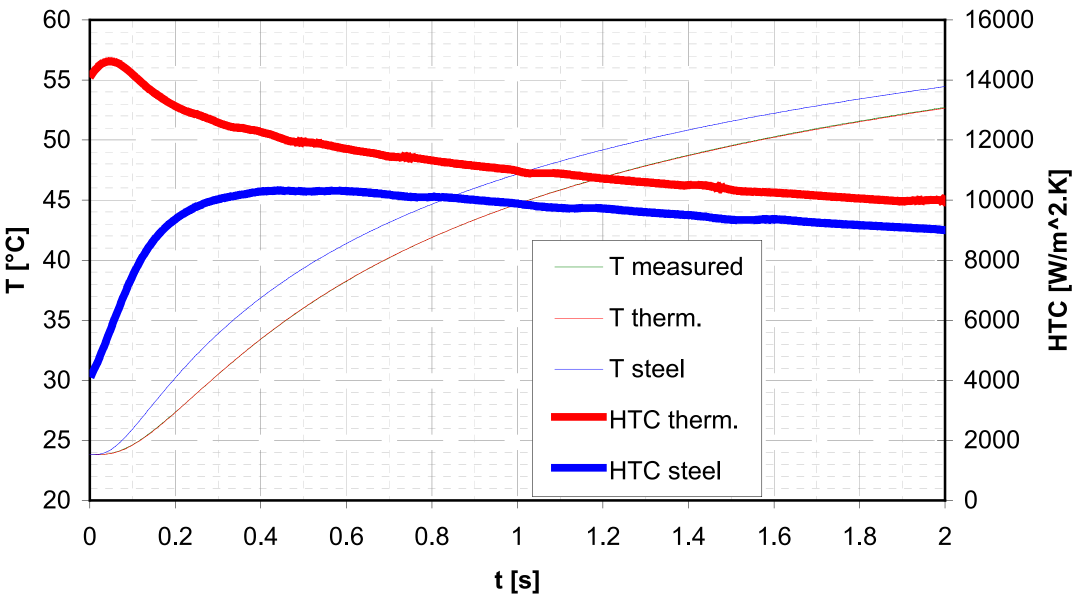

Figure 9 – Comparison of the results computed using two models – one made of homogeneous steel and the calibrated one with built-in thermocouple

obvious that the response of such a sensor would be somewhat faster.

In addition, HTC were computed on the heated side of the sensor during the experiment described in the previous paragraph (see Figure 9). An inverse task [6] computed the HTC using both the calibrated model and the homogeneous steel model *HTC therm.* and *HTC steel*, respectively. The heated copper and grease were supposed as the surrounding medium. The ambient temperature was the temperature of the copper. It is obvious that the computation with the homogeneous steel model failed at the beginning because there is no reason why HTC should be the lowest. HTC must be the highest at the beginning because the temperature gradient in the heated copper rod is the lowest. Therefore the heated copper rod is the most intensive source of heat. As the temperature gradient increases in the heated copper, the HTC decreases because the colder part of the copper is becoming a temperature resistor through which the heat must get.

7. Conclusion

In this paper, an experiment used for sensor calibration has been described. The calibrated sensors are used for measurements where HTC are investigated. Measurements from the sensor calibration experiment were used to calibrate the computational model. The Downhill Simplex optimization method was used for optimizing the parameters of the computational model.

The importance of the calibration of the model has been shown. Using a not calibrated model we would get HTC of different magnitude and a totally different shape of the computed HTC curve.

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