Int J Thermophys (2008) 29:915–925
DOI 10.1007/s10765-008-0418-9

Inhomogeneity Measurements of Long Thermocouples using a Short Movable Heating Zone

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Published online: 2 April 2008

Abstract The thermoelectric inhomogeneity of wires is one of the main components of the measurement uncertainty when using thermocouples. During calibration, it is therefore important to determine how much the inhomogeneities affect the measurement result. Thermoelectric inhomogeneity is normally assessed by gradual, or stepwise, insertion of a thermocouple into a furnace or liquid bath. With this type of equipment, the length that can be scanned is typically limited to about half a meter. To assess thermoelectric inhomogeneity over greater lengths, it is necessary to adopt a different technique. Therefore, an apparatus with a short, movable heating zone has been set up and evaluated. The apparatus produces a short, well-defined heating zone that is moved along the thermocouple while both the measuring and reference junctions are kept at 0 °C. Heating is done by means of a hot-air fan that produces a temperature-controlled heating zone up to 700 °C. Two directionally controllable cold-air fans, one on each side of the heating zone, make it possible to vary the slopes of both temperature gradients of the heating zone. Two temperature gradients influence the thermocouple when performing measurements of inhomogeneity with this setup. The results are, therefore, not directly comparable to the results from measurements taken in a bath or furnace, where only one temperature gradient is present. The resulting curve obtained with the two gradients is approximately equivalent to the derivative of the curve obtained with one gradient. It is possible to convert the two-gradient curve to a single-gradient curve by numerical integration, as shown in this work. Comparisons with inhomogeneity measurements obtained using salt baths show good agreement with the calculated results.

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Keywords Calibration · Heat treatment · Inhomogeneity · Method · Temperature · Thermocouple · Thermometer

1 Introduction

Thermocouples of different types and sizes are widely used by industry for high-temperature measurements. Exposure of thermocouples to elevated temperatures and/or chemical contamination at high temperatures often leads to compositional inhomogeneities of the thermocouple material, resulting in thermoelectric inhomogeneity of the wires. These inhomogeneities are one of the main components of the measurement uncertainty and must be taken into consideration for accurate measurements. During calibration, it is therefore important to determine how much the inhomogeneities affect the measurement result. This is normally determined by gradual, or step-wise, insertion of thermocouples into furnaces or liquid baths [1–3]. With this equipment, it is only possible to scan a length of about half a meter. Unfortunately, many industrial applications require longer thermocouples and it is therefore necessary to use a different technique. The fundamental embodiment of this kind of measurement is an apparatus with a short, movable heating zone [3–5]. In this work, the heating zone is achieved with a temperature-controlled hot-air fan.

2 Background

2.1 Inhomogeneity in Thermocouples

A thermocouple consists, in principle, of two homogeneous metal wires of dissimilar materials that are connected at one end (the measuring junction). When there is a temperature difference between the measuring junction and the reference junction (often 0 °C in an ice bath), a small voltage appears between the wires at the reference junction. This voltage is then conveyed to the voltage-measuring instrument by wires of identical composition (usually copper). If dissimilar materials of the metal wires of the thermocouple are homogeneous with respect to their thermoelectric properties, then the voltage difference depends only on the temperature difference between the measuring junction and the reference junction. If the wires are not homogeneous, the measured thermoelectric voltage depends not only on the temperature difference between the measuring junction and the reference junction, but also on the position of the temperature gradient along the wires. This is because the emf is not formed at the reference junction, but wherever temperature gradients occur between the reference junction and the measuring junction. Therefore, to measure inhomogeneity effects, it is necessary to expose the thermocouple to a defined temperature gradient [3,6].

2.2 Measurements in Liquid Baths and Furnaces—One Gradient

The most common method to assess thermoelectric inhomogeneity is to slowly move the thermocouple into or out of a liquid bath or a furnace. In this case, the thermocouple is exposed to a steep temperature gradient at the air/liquid interface or at the entrance to the furnace. A temperature gradient, typically from room temperature to some higher temperature, affects the thermocouple. The information obtained from this ‘immersion profile’ shows the influence of the inhomogeneity of the thermocouple in a direct way, giving a good appreciation for the thermocouple behavior in a practical situation. If the thermocouple under test is inhomogeneous, the immersion profile indicates where the inhomogeneities are located and how much the emf is influenced at different depths of immersion. Since a bath and a furnace have different gradients, the inhomogeneity assessment of a thermocouple will depend on the equipment used to obtain the immersion profile. Therefore, the influence of inhomogeneity is normally larger for measurements in a bath, which tends to have a much sharper temperature gradient compared to a furnace.

2.3 Measurements with a Short Movable Heating Zone—Two Gradients

Another way to assess inhomogeneity is to keep the thermocouple fixed and instead move a short, heated zone along the thermocouple. This will expose the thermocouple to two temperature gradients, one on each side of the heated zone. At the positions of the temperature gradients, voltages will be generated in the thermocouple. Because the temperature gradients are reversed, the two emfs will be of opposite polarity. If there are no inhomogeneties in the thermocouple at the positions of the temperature gradients (the Seebeck coefficients are the same), the two emfs will have the same magnitude and the net result will be zero. However, if there are any inhomogenity differences that affect the Seebeck coefficients in the two positions, the emfs will not be the same and we will measure a resulting emf that deviates from zero. The emf curve from measurements made with a two-gradient heating zone will not give as direct an indication of the emf generated at different depths of immersion, for practical measurements, as the one-gradient measurement. If both the thermocouple measuring junction and reference junction are kept at 0 °C, the emf will differ from zero when an inhomogeneous portion of thermocouple passes through the gradients of the heating zone. The resulting emf as a function of the position of the heating zone is actually a measure of the derivative of the emf for the one-gradient case. The reader is referred to Fig. 1, where examples of one- and two-gradient emf curves are given. The heights of the peaks in the emf curve are not directly comparable to the corresponding peaks in the curve from a one-gradient measurement. Nevertheless, the position of the peaks on the curve and the relative sizes indicate the extent of the thermocouple homogeneity and the location of the inhomogeneities. In order to estimate the effect on the emf from the thermocouple inhomogeneity at a certain temperature, the two-gradient curve has to be recalculated as a one-gradient curve corresponding to a measurement in a liquid bath or a furnace.

3 Equipment

3.1 Design of Equipment

The equipment is based on the principle of measuring the deviation from zero emf when a short, well-defined heating zone is moved along the thermocouple, while

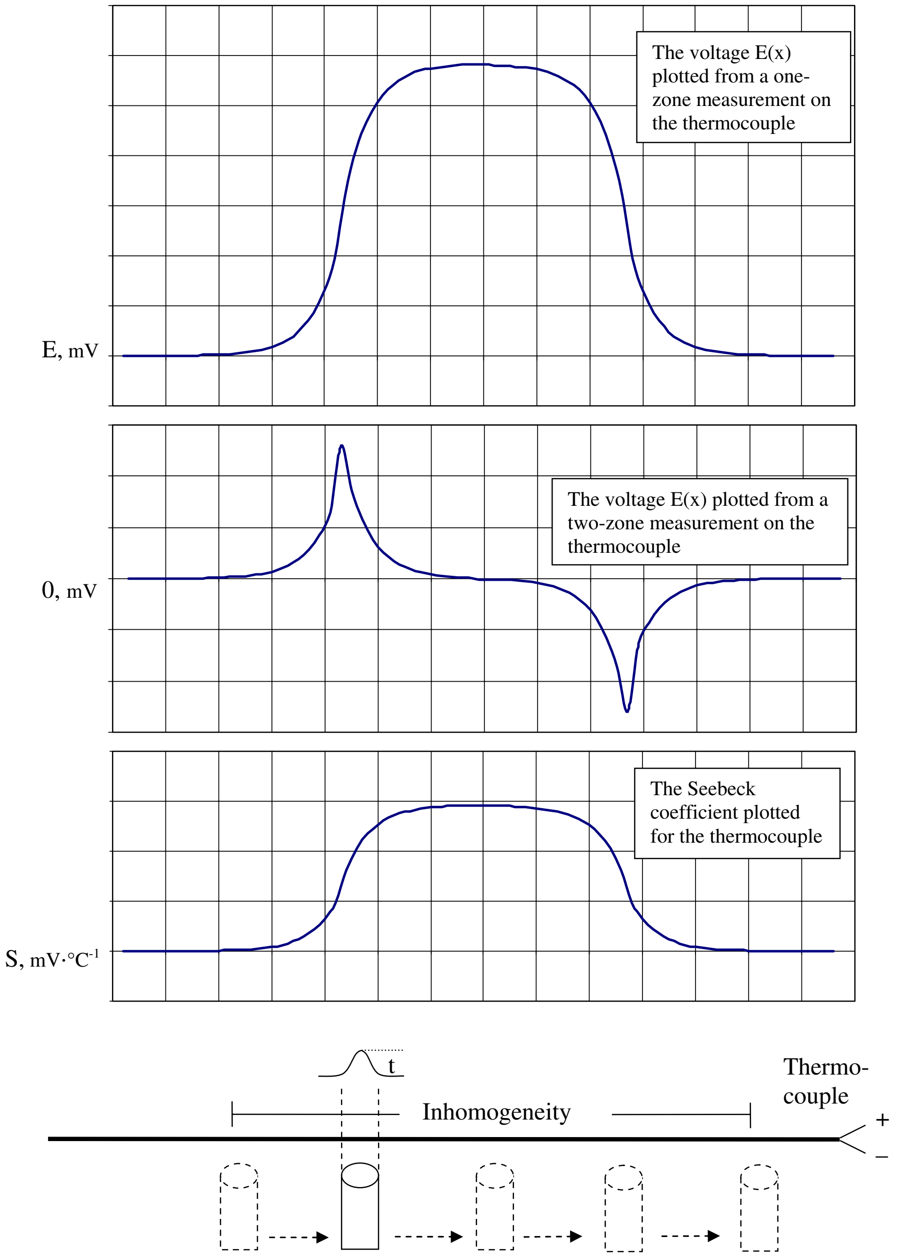

Fig. 1 Figure shows the movable heating zone at five different positions along the thermocouple during a measurement. Above are the corresponding plots for a one-gradient measurement and a two-gradient measurement, respectively

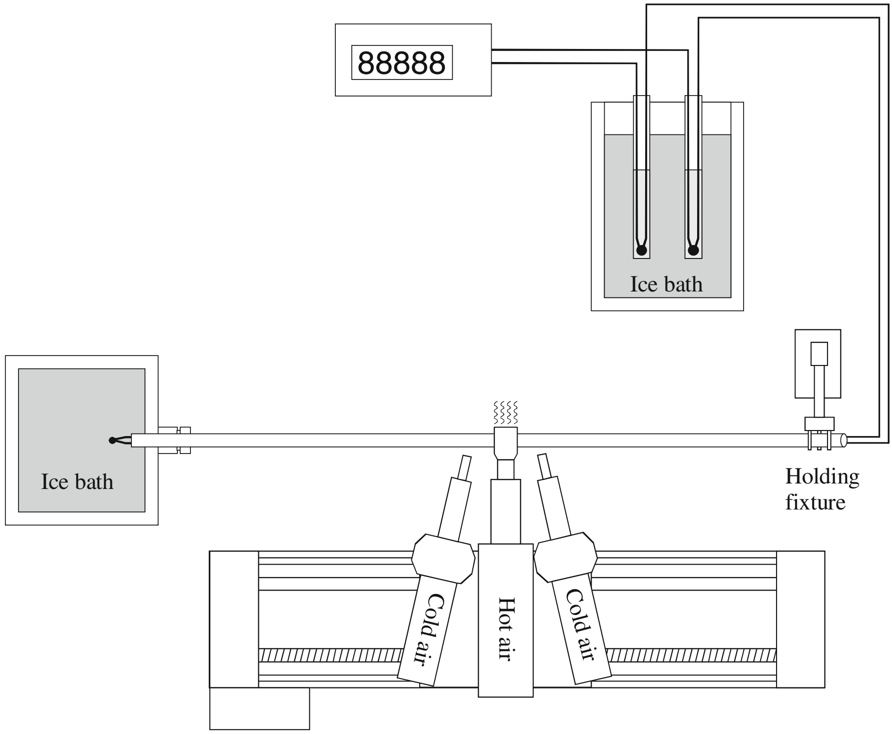

Fig. 2 Schematic representation of the measuring equipment for inhomogeneity determination using a movable zone

both the reference junction and measuring junction are kept at 0 °C. To produce rapid heating over a limited length of the thermocouple, a high-temperature heating fan (max 700 °C) is used with an outlet nozzle of 45 mm diameter to guide and limit the air flow. On each side of this nozzle, a fan with guiding nozzles blows cold air to cool the thermocouple outside of the heating zone (see Fig. 2). The cooling fans, adjustable in orientation, perform the task of producing temperature gradients that are as steep as possible from ambient temperature to the maximum of the hot zone and back again to ambient. An example of the actual temperature gradients is shown in Fig. 5. The three fans are mounted on a horizontal moveable slide, which is fastened to a linear positioning unit controlled via a stepping motor connected to a computer. The linear positioning unit has a length of 1.4 m, but arbitrary lengths can be obtained. The temperature of the hot air is thermostatically controlled and continuously variable. This temperature is measured with a thermocouple placed in the center of the airflow, close to the investigated thermocouple. Both of the thermocouples use ice baths (0 °C) as their reference temperature and connect to a scanner and then to a nanovoltmeter and computer. To be able to make controlled and precise movements, a control and measuring program was developed for the computer. It permits scanning in both directions with selectable step size and scanning time. The emfs of the thermocouple under test and the thermocouple measuring the temperature of the hot air

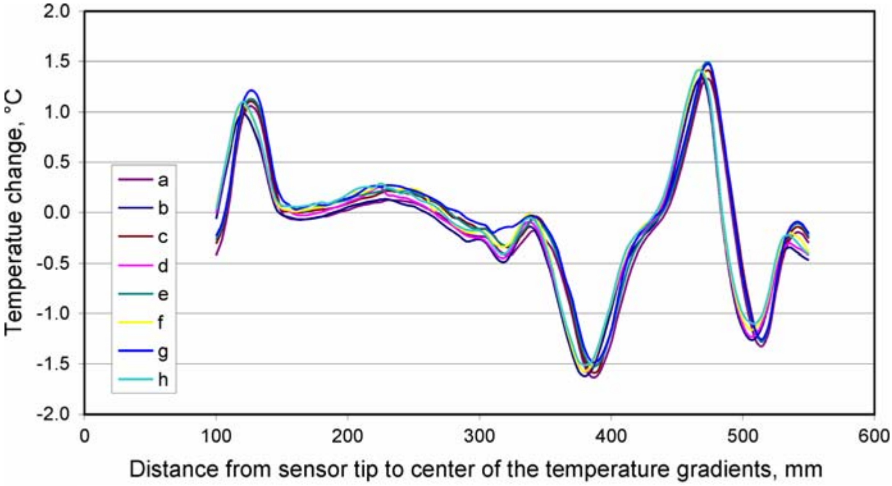

Fig. 3 Multiple measurements of a MIMS Type K thermocouple at 300 °C showing the reproducibility of the inhomogeneity equipment

are recorded by the computer and can be graphically displayed during the measurement.

4 Measurements

4.1 Reproducibility

A number of measurements were made in order to examine the effects of different scanning times and step sizes and to assess the reproducibility of the method. In Fig. 3, a compilation of eight runs is shown for a MIMS thermocouple of Type K. Four of the runs were scanned from the tip of the thermocouple in the ice container towards the stand, which supports the other end of the thermocouple, and the other four runs were done in the opposite direction. In the figure, the runs a, c, e and g are measured from the tip. Each measurement is performed with a total scanning time of 20 min for a scanning length of 450 mm and a step size of 5 mm. As seen in the figure, the dispersion is small between the runs, and a single measurement provides a good understanding of the thermocouple inhomogeneity.

The scanning time was also investigated by scanning a 450 mm long section with scanning times of (10, 20, 30, 40 and 60) min. From 20 min and above, no significant differences were observed.

4.2 Comparison Between Movable Heating Zone and Bath

4.2.1 Measurements with a Short Movable Heating Zone

A used MIMS type K thermocouple was measured with the movable heating-zone method. The scanning time was 20 min and the temperature of the heating zone

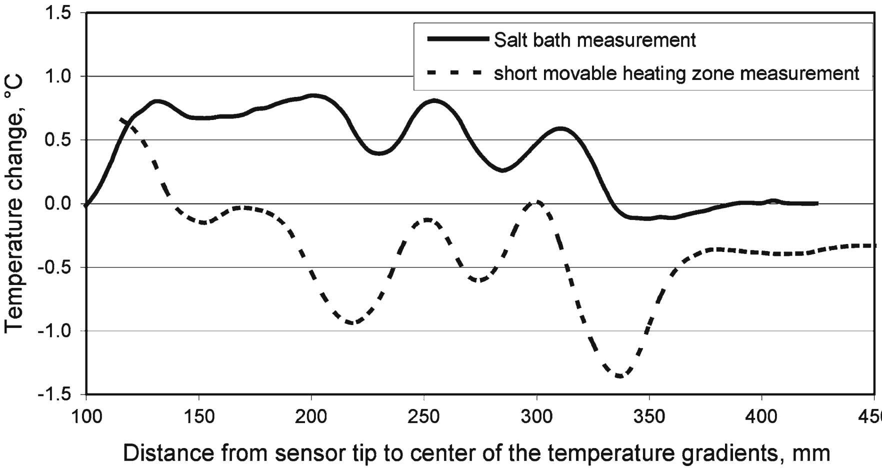

Fig. 4 Comparison for a MIMS Type K thermocouple between the one-gradient measurement in a salt bath and the two-gradient measurement with the movable heating zone

was 300 °C. The measured voltage, converted to temperature, is presented in Fig. 4 as a dashed curve. As can be seen, inhomogeneties affect the output of the thermocouple.

4.2.2 Measurements in a Liquid Bath

The same thermocouple was measured at 300 °C by immersing it in a step-wise manner into a salt bath. At every step, the emf was recorded after the thermocouple came to equilibrium. In this case, the thermocouple was exposed to a steep temperature gradient near the liquid interface. The resulting voltage, converted to temperature and presented as a deviation from a nominal value, is indicated in Fig. 4 as a solid line. During the measurement, a reference thermometer monitored the bath temperature.

4.2.3 Measurement Uncertainties

The uncertainty components for a single measurement point in the movable heating-zone measurement arise mainly from the ice baths, the scanner, the nanovoltmeter and the temperature change in the heated zone. By analysing the components and including the standard deviation of the measurements, an expanded uncertainty of ±0.09 °C ($k = 2$) is estimated for a single measurement point.

An inhomogeneity that gives rise to a slow change in the Seebeck coefficient will be hard to resolve with the movable heating-zone method. The uncertainties given above do not include the evaluation discussed in Sect. 5. The evaluation is based on several single measurements, which leads to an increased uncertainty.

5 Evaluation

5.1 Interpreting the Results from the Measurements with a Movable Heating Zone

As stated in Sect. 2, it is not possible to directly obtain, from the results with the movable heating zone, the correct magnitude of the influence on the emf due to the thermoelectric inhomogeneity. The heating zone has two closely positioned gradients that affect the thermocouple instead of only one as is the case for measurement in a furnace or liquid bath. The curves from the two-gradient case approximate in some way the derivative of the corresponding curves from the one-gradient case (see also Fig. 1). Therefore, it is necessary to numerically transform the two-gradient curve to obtain a curve that corresponds to the one-gradient case. It is also necessary to make some corrections that depend on the actual thermocouple and the equipment that is used. Below is an evaluation of the measurement of the MIMS thermocouple presented in Sect. 4.

5.2 Evaluation of a MIMS Thermocouple

5.2.1 Offset Compensation of Result from the Movable Heating Zone Method

When a measurement is made with the movable heating zone method, an offset error that depends on the possible difference in the Seebeck coefficient near the tip of the thermocouple compared with the part of the thermocouple or extension wire that is connected to the voltmeter. When both these points are placed in ice baths, they generate an emf corresponding to the temperature difference between 0 °C and ambient temperature. For an ideal thermocouple, these emfs are of the same magnitude and will therefore cancel, but in practice there can be a slight difference. This voltage difference results in an offset error unique to each thermocouple. This offset error shifts the measured curve in the vertical direction.

5.2.2 Estimation of the Positions of the Gradients for the Movable Heating Zone Method

When performing a run with the movable heating zone method, two temperature gradients, t_{g1} and t_{g2}, occur, one on each side of the nozzle of the heating fan (see Fig. 5). In order to recalculate the result, it is necessary to analyse the geometry of the gradients at the measurement site. As the equipment moves step by step, a sequence of measured values that are related to the position of the nozzle is obtained. In Fig. 5, the temperature gradients along the thermocouple are shown for a given position (x_m) of the nozzle. We suppose that the recalculation starts from an unaffected, homogeneous part of the thermocouple's two-gradient curve. When the Seebeck coefficient has different values for the parts of the thermocouple affected by the temperature gradients, t_{g1} and t_{g2}, the voltmeter deviates from zero. The gradients have, as we know, same appearance and size, but appear with opposite sign. In order to start a calculation, you

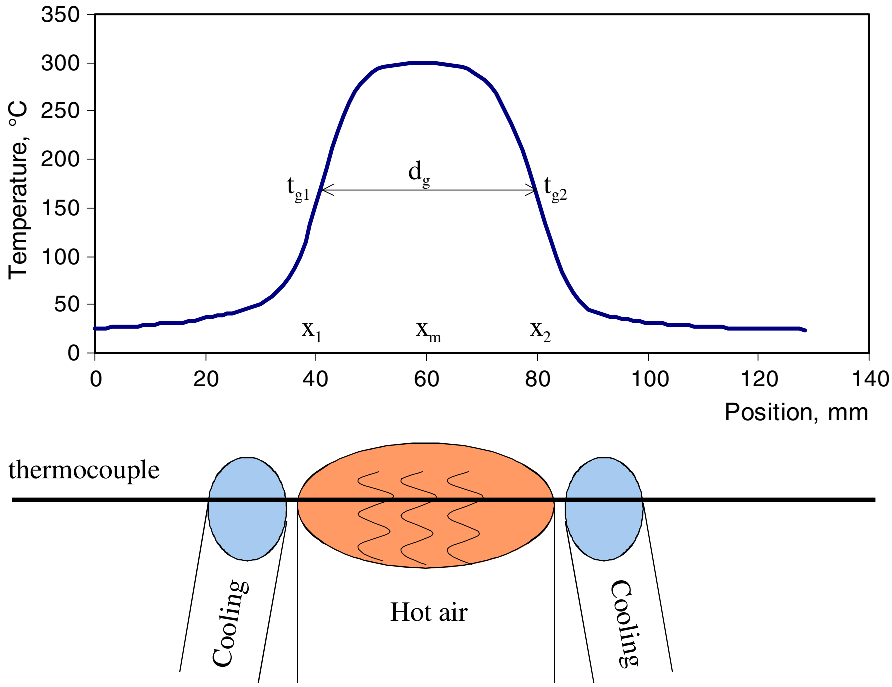

Fig. 5 Analytic representation of the two-gradient model. The temperature gradients are measured for a 3 mm MIMS thermocouple at 300 °C

need some sort of starting value. The starting value of the emf can be established from a measurement in a liquid bath or furnace. If the absolute value of the emf is not of interest, but rather the size of the emf variation caused by the inhomogeneity, an emf value from a reference table for the actual temperature and type of thermocouple can be used as the starting value.

In order to calculate the emf at position x_2, it is necessary to determine where in the measured sequence the value corresponding to the emf-difference between position x_1 and position x_2 should be obtained. This is the value when the heating fan is in position x_m, where the measured emf represents the difference in the influences of the respective temperature gradients ($t_{\mathrm{g}1}$ and $t_{\mathrm{g}2}$) on the thermocouple. This emf value adds to the absolute emf at position x_1, which at the start is the measured reference emf. In order to choose the correct emf value at position x_m, it is necessary to know the distance between the gradients, d_g, in Fig. 5. Note that the incremental steps are much smaller than d_g. As both gradients move along the thermocouple, the first calculated absolute emf value will be the starting point for the next calculation, and so on.

5.2.3 *Shift of Gradient Depending on Direction and Speed*

This discussion presupposes that the temperature gradients in the curve are symmetrically placed in relation to the position of the nozzle. By comparing measurements when the hot-air fan is moving towards and away from the tip of the thermocouple, it can be seen that the curves are shifted in relation to each other. This means that there is a slight shift in the temperature gradients that depends on the speed of the nozzle of the heating fan. To perform as correct a calculation as possible, it is necessary to compensate for this shift.

5.2.4 Determination of the Reference emf

As shown in Sect. 5.2.2, a reference emf is needed when recalculating the results from the movable heating-zone measurements. This reference value is determined from the calibration. The calibration equipment should have a well-defined temperature gradient, since the position along the thermocouple to which the reference emf corresponds must be known. Therefore, the calibration is best done in a liquid bath.

5.2.5 Determination of the Position of the Gradient in the Salt Bath

For measurements in the salt bath, we have used the distance between the tip of the thermocouple and the surface of the liquid. This may not be the best estimate of the position of the gradient to which the thermocouple is exposed; the effective gradient is situated slightly above the surface of the liquid. To recalculate the results from the movable heating zone measurements as accurately as possible, this shift in the position of the gradient must be taken into consideration.

6 Results

To check the calculation procedure, the results from one of the movable heating zone measurements presented in Sect. 4 have been calculated according to the principles presented in Sect. 5. The resulting comparison is shown in Fig. 6. The recalculation assumes the following:

Temperature: 300 °C
Offset emf for the hot-air measurement: −0.40 °C
Estimated distance between the gradients of the hot-air method: 40 mm
Shift of gradient depending on the direction and speed of the hot-air fan: 5 mm
Reference temperature from the salt bath: 299.1 °C
Gradient shift in the salt bath compared with the liquid level: 15 mm

As can be observed from Fig. 6, the two curves correspond rather well. The result shows that it is possible to recalculate the measurement data for a movable heating zone to predict how a thermocouple will behave in a practical measurement. In the future, it should be possible to further refine the calculation procedure.

Very precise measurements of thermoelectric inhomogeneity are difficult because each measurement affects the thermocouple. By making a measurement, some sort of heat treatment of the thermocouple occurs, which may influence the inhomogeneity. The movable heating zone method may affect the thermocouple less than the measurements in baths and furnaces, but this should be investigated further.

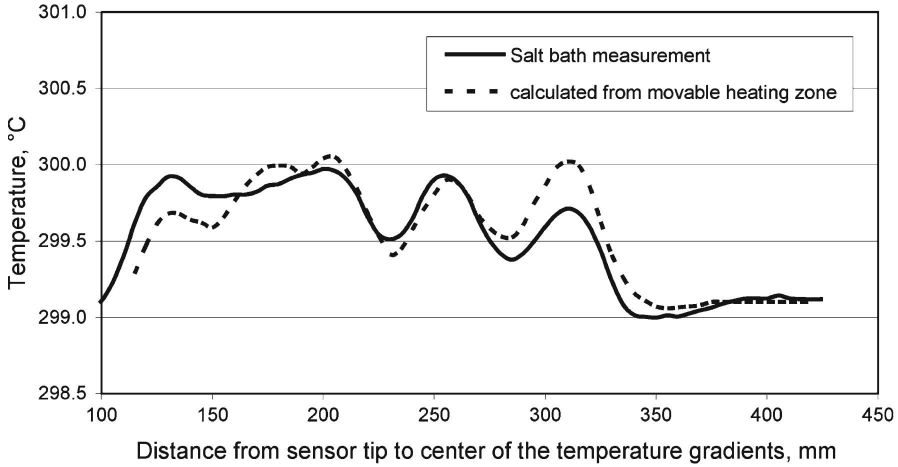

Fig. 6 Comparison between the effect of the inhomogeneity measured in the salt bath and the corresponding calculation from the movable heating zone result for a MIMS Type K thermocouple

Acknowledgments This work was supported in part by the Nordic Innovation Centre in the Project No. 04040 *Measuring inhomogeneities of thermocouples*. The project group consisted of J. Ivarsson (project leader), R. Falk, M. Holmsten, M. Lidbeck, G-M. Löfdahl, SP, Sweden, T. Weckström, MIKES, Finland, F. Helgesen, Justervesenet, Norway and F. Andersen, Risø, Denmark.

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