



Correlation Between Insulation Resistance and Temperature Measurement Error in Type K and Type N Mineral Insulated, Metal Sheathed Thermocouples

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Abstract

Mineral insulated, metal sheathed (MI) Type K and Type N thermocouples are widely used in industry for process monitoring and control. One factor that limits their accuracy is the dramatic decrease in the insulation resistance at temperatures above about 600 °C which results in temperature measurement errors due to electrical shunting. In this work the insulation resistance of a cohort of representative MI thermocouples was characterised at temperatures up to 1160 °C, with simultaneous measurements of the error in indicated temperature by *in situ* comparison with a reference Type R thermocouple. Intriguingly, there appears to be a systematic relationship between the insulation resistance and the error in the indicated temperature. At a given temperature, as the insulation resistance decreases, there is a corresponding increasingly negative error in the temperature measurement. Although the measurements have a relatively large uncertainty (up to about 1 °C in temperature error and up to about 10 % in insulation resistance measurement), the trend is apparent at all temperatures above 600 °C, which suggests that it is real. Furthermore, the correlation disappears at temperatures below about 600 °C, which is consistent with the well-established diminution of insulation resistance breakdown effects below that temperature. This raises the intriguing possibility of using the as-new MI thermocouple calibration as an indicator of insulation resistance breakdown: large deviations of the electromotive force (emf) in the negative direction could indicate a correspondingly low insulation resistance.

Keywords Insulation resistance breakdown · Mineral insulated metal sheathed thermocouple · Temperature · Thermocouple · Thermoelectric

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1 Introduction

In essence a thermocouple consists of two dissimilar metal wires (thermoelements) connected at one end (the measurement junction). When the thermocouple is exposed to a temperature gradient, an electromotive force (emf) is generated, and this can be measured and converted into a temperature reading.

Thermocouples are one of the most widely used temperature sensors, with swaged base metal mineral insulated, metal sheathed (MI) thermocouples being the most commonly used in industry [1]. These thermocouples consist of the aforementioned thermoelements, surrounded by an electrically insulating material (usually crushable magnesium oxide), encased in a sheath made of metal such as stainless steel or Inconel.

An accurate temperature measurement relies on the thermoelements being connected only at the measurement junction. As the temperature increases, the conductivity of the insulation increases, with a corresponding decrease in the resistance between the thermoelements as a result of the decreasing resistivity of the magnesium oxide [2]. In addition, magnesium oxide is hygroscopic, and any absorbed moisture also reduces its resistivity. Both these effects result in an electrical shunt along the affected length of the thermocouple. This can cause temperature measurement errors, because the decreased resistance results in a delocalisation of the measurement junction away from the hot region and the thermocouple will indicate a temperature which is too low [3]. This phenomenon is referred to in this paper as ‘insulation resistance breakdown’. As the effect can cause errors of the order of degrees, and is generally more pronounced for thinner MI thermocouple cable [2, 4], the ASTM E608 [5] standard provides guidance on the maximum temperature of use for a given MI thermocouple cable diameter.

It is of great interest for thermocouple manufacturers to establish some practical way of characterising insulation resistance breakdown that does not rely on measuring the insulation resistance of each thermocouple. In this paper an investigation of insulation resistance effects in MI Type K and N thermocouples in the as-received state, performed at the National Physical Laboratory (NPL, UK) and Centro Español de Metrología (CEM, Spain), is presented. Section 2 describes the experimental setup and measurement protocol. Section 3 presents the results of the investigation and a discussion. Some conclusions are drawn in Sect. 4.

2 Experimental Setup

2.1 CEM

A cohort of 14 MI Type K and N thermocouples (IEC 60584-1 [6] Class 2 tolerance) with cable diameters ranging from 0.75 mm to 6 mm was assembled. These were sourced from the same manufacturer. These were four Nicrotherm sheathed Type N thermocouples, five Inconel 600 sheathed Type K thermocouples, and

five Inox AISI 310 sheathed Type K thermocouples. The ceramic insulation material was MgO. All thermocouples were from different lots.

The resistance measurements cover the range from 1 k Ω to 1000 G Ω . The lower resistance values were measured with an 8.5 digit Keysight 3458A digital multimeter, and resistances higher than 1 G Ω were measured with a sub-fA Keithley 6430 with its 'remote preamp' configuration. The thermocouple insulation resistance was taken to be the resistance between the thermocouple sheath (adjacent to the head at the cold end) and one of the thermoelements.

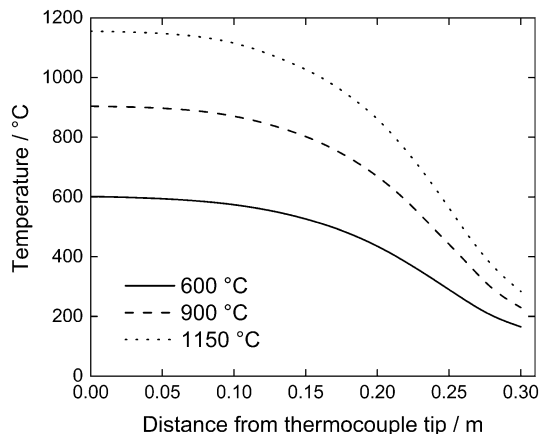
The thermocouples were placed in a three-zone Isotech 465 furnace with an isothermal block, and the measurements were performed at decreasing temperatures. Prior to the measurements, which started at 1100 °C, the thermocouples were subjected to an overnight heat treatment at 1100 °C. The temperature of the furnace was determined using a calibrated Type R thermocouple for temperatures higher than 1000 °C and Au/Pt thermocouples for lower temperatures, both using alumina insulation tubes. The measurements were performed with the reference junction of the thermocouples in a crushed ice-water mixture. The uncertainty of the reference thermocouple measurements (coverage factor $k=2$, corresponding to coverage probability of 95 %) was ± 0.45 °C (Type R) and ± 0.20 °C (Au/Pt).

2.2 NPL

A cohort of 12 MI Type K and N thermocouples (IEC 60584-1 [6] Class 1 tolerance) each having cable diameters of 1 mm, 2 mm and 3 mm was assembled. Two manufacturers supplied six thermocouples each (three Type K, three Type N). The ceramic insulation material was MgO. All thermocouples were from different lots.

The MI thermocouple under test was inserted into an alumina worktube (70 mm inner diameter), insulated internally with alumina brick and ceramic wool, which was then placed in an Elite three-zone furnace. The temperature profile of the furnace is shown in Fig. 1. The thermocouple was connected, via a reference junction, to an Agilent 34970A multimeter to measure the emf. The reference junction was kept at 0 °C

Fig. 1 Temperature profile along the furnace at three representative furnace temperatures



using a Fluke 9101 zero-point dry well. Connected to other channels on the multimeter, which could measure a maximum resistance of 100 M Ω , were the wires used to measure the resistance between the outer sheath (adjacent to the head at the cold end) and one of the thermoelements. A calibrated Type R reference thermocouple (using alumina insulation tubes) was also connected and placed alongside the MI thermocouple with the same immersion depth to determine the error in the indicated temperature of the MI thermocouple *in situ*. The uncertainty of the reference thermocouple measurements (coverage factor $k=2$, corresponding to coverage probability of 95 %) was ± 0.3 °C from 0 °C to 1100 °C, rising to ± 0.55 °C at 1330 °C.

All results presented here were measured during cooling, rather than warming, to avoid electrical interference effects from furnaces, and hysteresis effects related to the complex phenomena associated with conducting ceramics [7, 8].

3 Results

3.1 Temperature Dependence of the Insulation Resistance

The temperature dependence of the insulation resistance for the CEM thermocouples is shown in Fig. 2a. As expected [2, 9], the resistance decreases approximately exponentially with temperature, and generally increases with increasing thermocouple cable thickness. This can be seen in Fig. 2b, which shows how the resistance varies with cable diameter for the Inconel sheathed Type K thermocouples. It can be seen in Fig. 2b that the resistance increases asymptotically with cable thickness up to a diameter of 3 mm, then changes only slightly beyond that for larger cable diameters. The measurements at CEM showed that, as expected, the thermometer type (K or N) and sheath material have no bearing on the insulation resistance. The data shown in Fig. 2b is generally representative of all the thermocouples tested, except for the NPL Type K and Type N thermocouples, which, for reasons that are not clear, both showed non-monotonic behaviour of the resistance as a function of thermocouple thickness. This does not invalidate the following results because the figure of merit representing the insulation is its resistance, not the cable thickness. Figure 2c and d show the insulation resistance of the NPL thermocouples as a function of resistance; it can be seen that thermocouple K2A is anomalous, and this thermocouple was excluded from the analysis.

3.2 Relation Between Indicated Temperature Error and Insulation Resistance

The temperature, t , indicated by Type K and Type N thermocouples with diameters of 1 mm, 2 mm and 3 mm was measured at NPL during the insulation resistance measurements, and compared *in situ* with a calibrated reference Type R thermocouple. The difference between the temperature indicated by the two thermocouples,

$$\Delta t = t(\text{MI thermocouple}) - t(\text{Type R reference thermocouple}),$$

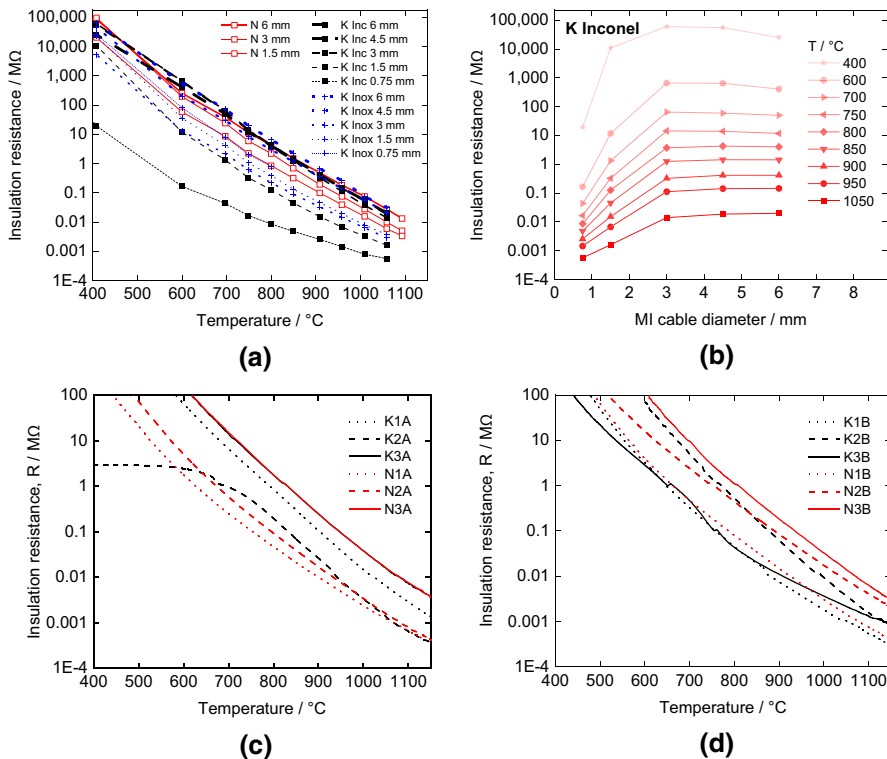


Fig. 2 (a) Insulation resistance as a function of temperature of the MI thermocouples measured at CEM for Inconel sheathed Type N thermocouples (N), Inconel sheathed Type K thermocouples (K Inc) and Inox AISI 310 sheathed Type K thermocouples (K Inox). One Type N thermocouple is not presented as it showed anomalous behaviour. The dimensions indicate the MI cable diameter. (b) Dependence of the insulation resistance on cable diameter for the Inconel sheathed Type K thermocouples measured at CEM. (c, d) Insulation resistance as a function of temperature for the NPL thermocouples from supplier A and B, respectively; here it can be seen that the measurements for thermocouple K2A are anomalous, and these are excluded from the analysis

is shown in Fig. 3. Δt is hereafter taken to be the temperature measurement error of the MI thermocouples. The maximum change of Δt (i.e., the difference between the values at the lowest and highest temperatures) is shown in Table 1.

Note that thermoelectric drift of the MI thermocouples was not significant over the relatively short duration of these tests (a few hours) as evidenced by the high degree of reproducibility during the warming and cooling stages. Therefore drift can be ruled out as a cause of the observed behaviour reported in this study.

To examine whether there is any relationship between the insulation resistance, R , and the measured temperature error Δt , the two are plotted against each other in Fig. 4. To achieve sufficiently good statistical quality, the values of R and Δt shown in Fig. 4 are the average values over a temperature range extending 5 °C either side of the nominal temperature, i.e., the nominal temperature ± 5 °C (except for the measurements at 1160 °C where the temperature was

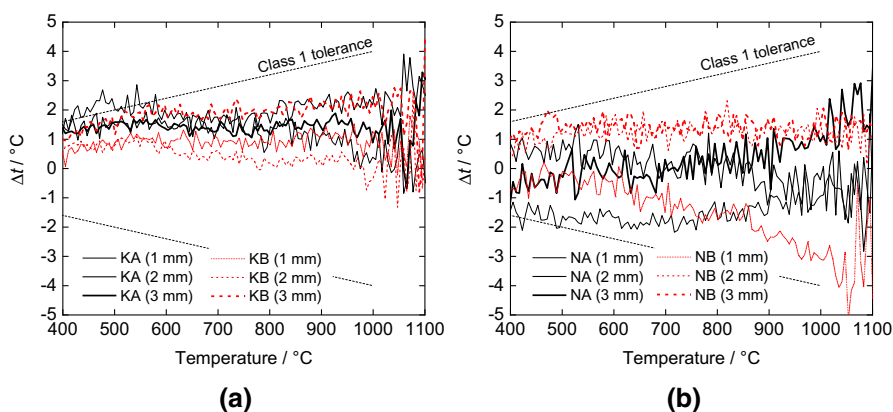


Fig. 3 Indicated temperature measurement error of the MI thermocouples at NPL, Δt , as a function of temperature, for the thermocouples from Supplier A (solid black lines) and Supplier B (dashed red lines). (a) Type K thermocouples. (b) Type N thermocouples. “KA”, “KB”, “NA” and “NB” refers to Type K and Type N thermocouples from Supplier A and B, respectively

Table 1 Variation of the temperature error, Δt , between 400 °C and 1160 °C for each of the NPL thermocouples

Thermocouple	Type	Diameter / mm ⁻¹	Δt at 400 °C / °C	Δt at 1160 °C / °C	Change in Δt / °C
K1A	K	1	1.2	−1.2	2.4
K2A	K	2	1.3	−2.4	3.7
K3A	K	3	1.4	−3.3	4.6
K1B	K	1	0.6	−3.5	4.1
K2B	K	2	0.5	−3.3	3.8
K3B	K	3	1.0	−0.8	1.8
N1A	N	1	−1.5	−1.7	0.1
N2A	N	2	0.9	−4.2	5.1
N3A	N	3	−1.2	0.2	−1.4
N1B	N	1	−0.7	−7.8	7.1
N2B	N	2	0.6	−3.8	4.5
N3B	N	3	1.0	0.5	0.5

held constant, and about 1000 readings were available), and the standard deviation over this range was also recorded and presented as error bars in Fig. 4. In some cases (500 °C and 600 °C) the resistance was out of range of the multimeter, so in those cases only ΔT is plotted (shaded ellipses in Fig. 4); these values were ignored in subsequent curve-fitting. The linear fit to the data at each temperature suggests that there is a systematic trend of decreasing Δt with decreasing R —in other words, as the insulation resistance decreases, there is a corresponding increasingly negative error in the temperature measurement. Although

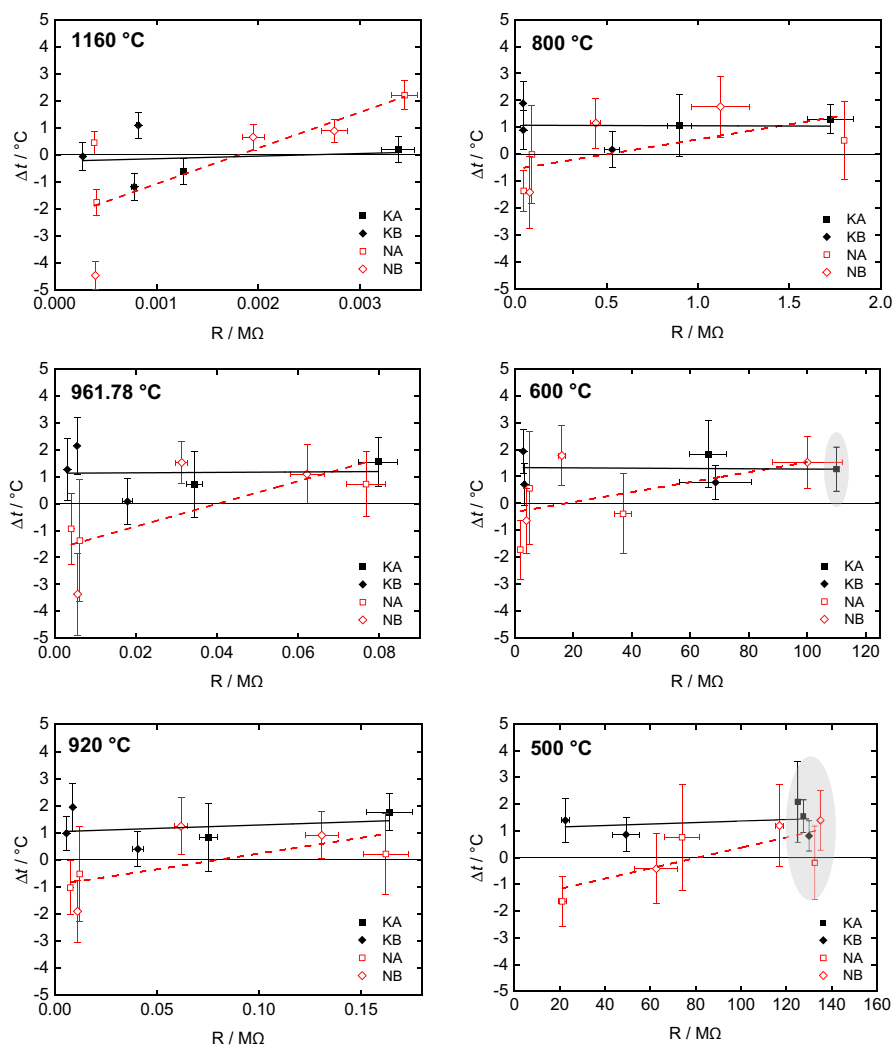


Fig. 4 Variation of temperature measurement error, Δt , as a function of insulation resistance, R , at six different temperatures. The straight line is a least-squares fit to Type K (black solid line) and Type N (red dashed line) thermocouple data (except those encircled, for which the insulation resistance was not measurable, so these are only included on the plots to show the values of Δt). It appears that Δt systematically decreases with decreasing R at all temperatures for both thermocouples; the effect is most pronounced at the highest temperature and becomes progressively—and systematically—less pronounced as the temperature decreases. Error bars correspond to the standard deviation of Δt and R , respectively, over the selected temperature range (which was the nominal temperature ± 5 °C). Legend is as in Fig. 3 (Color figure online)

the measurements have a fairly large uncertainty of the order of 1 °C in the temperature error and up to about 10 % of insulation resistance, the trend is apparent at all temperatures, which suggests that it is real, and not a statistical or random

artefact. In particular, Fig. 4 shows that, in general, the temperature error of the MI thermocouples is overwhelmingly positive when the insulation resistance is large; as the insulation resistance decreases, the occurrence of negative temperature errors becomes increasingly common.

Furthermore, in the temperature range where insulation resistance breakdown is expected to be significant (i.e., above about 600 °C) the point at which the best-fit line crosses the ordinate—which represents the ‘worst-case’ value of Δt in the limit of zero insulation resistance—increases systematically as the temperature decreases (Fig. 5) down to about 600 °C, and remains unchanged as the temperature decreases further, although the effect is considerably more pronounced for the Type N thermocouples than for the Type K thermocouples. It can be seen in Fig. 5 that this trend is well described by an exponential function (parameterised by least-squares fitting).

This is consistent with the decreasing importance of insulation resistance breakdown at lower temperatures. Indeed, it can be seen in Fig. 4 that at 500 °C, where the insulation resistance breakdown effect is negligible, the slope of the line is almost zero and most values of Δt are positive, that is, Δt no longer depends on R .

This raises the intriguing possibility of using the as-new calibration as an indicator of insulation resistance breakdown: a large deviation of the emf of a new MI thermocouple in the negative direction at temperatures above about 600 °C could indicate a correspondingly low insulation resistance. However, further

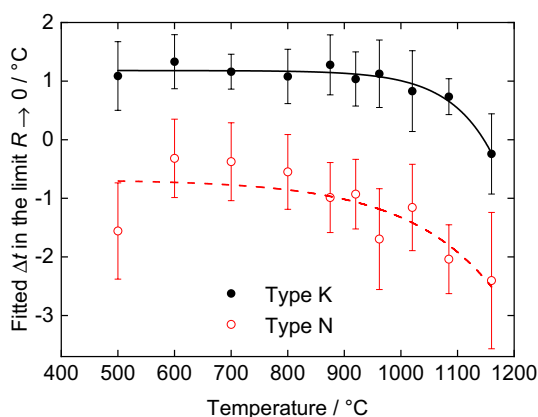


Fig. 5 Temperature dependence of the fitted Δt in the limit of zero insulation resistance (i.e., where the best-fit line crosses the ordinate at the five temperatures shown in Fig. 4) for Type K thermocouples (black closed circles) and Type N thermocouples (red open circles). The value of Δt at $R=0$ signifies the worst-case temperature measurement error arising from insulation resistance breakdown. The data show a systematic trend downwards as temperature increases, indicative of increasingly negative error in the temperature indicated by the thermocouple. There is no significant change at temperatures below about 600 °C. The fitted line is a fitted exponential function in each case. Error bars correspond to the standard uncertainty of the fitted value Δt where it crosses the ordinate, i.e., the constant term of the fitted line in Fig. 4 (Color figure online)

measurements with lower uncertainty are needed to demonstrate this conclusively and formulate a procedure.

4 Conclusion

The insulation resistance of a cohort of representative MI thermocouples has been characterised at temperatures up to 1160 °C, together with simultaneous measurements of the error in indicated temperature by *in situ* comparison with a reference Type R thermocouple. The results suggest a systematic relationship between the insulation resistance and the error in the indicated temperature at and above about 600 °C: at a given temperature, as the insulation resistance decreases, there is, in general, a corresponding increasingly negative error in the temperature measurement. Although the measurements have a relatively large uncertainty of the order of 1 °C, the trend is apparent at all temperatures at and above 600 °C, which suggests that it is a real. Furthermore, the effect disappears at temperatures below about 600 °C, which is consistent with the well-established absence of insulation resistance breakdown effects below that temperature.

This raises the intriguing possibility of using the as-new MI thermocouple calibration as an indicator of insulation resistance breakdown: anomalously large deviations of the emf in the negative direction could indicate a correspondingly low insulation resistance. Further work is needed to determine whether the observed trends are generally applicable, and if a technique based on the findings is feasible in practice.

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Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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