

PAPER • OPEN ACCESS

Thermoelectric stability of dual-wall and conventional type K and N thermocouples

To cite this article: D J L Tucker *et al* 2022 *Meas. Sci. Technol.* **33** 075003

View the [article online](#) for updates and enhancements.

You may also like

- [Updated measurement method and uncertainty budget for direct emissivity measurements at the University of the Basque Country](#)
I González de Arrieta, T Echániz, R Fuente et al.
- [A design exercise on temperature measurement](#)
J C Jones
- [The dynamical behaviour of type-K competitive Kolmogorov systems and its application to three-dimensional type-K competitive Lotka–Volterra systems](#)
Xing Liang and Jifa Jiang



NOW WITH MICROPL UPGRADE
FOR SPECTRAL AND TIME-RESOLVED
PHOTOLUMINESCENCE MICROSCOPY.



edinst.com

Thermoelectric stability of dual-wall and conventional type K and N thermocouples

D J L Tucker^{1,*} , F Edler² , V Žužek³, J Bojkovski³, C Garcia-Izquierdo⁴ , M Parrondo⁴, L Šindelářová⁵ and N Arifovic⁶

¹ National Physical Laboratory (NPL), Hampton Road, Teddington TW11 0LW, United Kingdom

² Physikalisch Technische Bundesanstalt (PTB), Abbestr. 2-12, 10587 Berlin, Germany

³ University of Ljubljana (UL), Tržaška cesta 25, SI-1000 Ljubljana, Slovenia

⁴ Centro Español de Metrología (CEM), Alfár 2, 28760 Tres Cantos, Madrid, Spain

⁵ Czech Metrology Institute (CMI), Okružní 31/772, 638 00 Brno, Czech Republic

⁶ Türkiye Bilimsel ve Teknolojik Arastırma Kurumu (TUBITAK), Gebze Yerleşkesi, 41470 Gebze, Kocaeli, Turkey

E-mail: declan.tucker@npl.co.uk

Received 25 November 2021, revised 2 February 2022

Accepted for publication 23 February 2022

Published 5 April 2022



CrossMark

Abstract

Mineral insulated metal sheathed (MIMS) base metal thermocouples experience thermoelectric drift over their lifetime caused by use at high temperatures and metallurgical changes, causing spurious measurement errors. CCPI Europe Limited and University of Cambridge have designed a MIMS thermocouple with an additional inner sheath, in order to protect the thermoelements from the effects that cause thermoelectric drift. The performance of these dual-wall thermocouples and conventional type N and type K thermocouples are assessed at six different National Metrology Institutes (NMIs) using two different testing regimes: isothermal testing at 1200 °C, and thermal cycling tests between 300 °C and 1150 °C. The investigation demonstrates that in both testing regimes, the type N dual-wall thermocouples showed a significantly reduced thermoelectric drift by about a factor of three compared to the conventional thermocouples. There was no significant difference between the type K dual-wall and conventional type K thermocouples in the isothermal tests, and the type K dual-wall thermocouples showed greater drift than the conventional thermocouples in the thermal cycling tests, but the conventional type K thermocouples were less robust than the dual-wall type K thermocouples. The results presented in this paper represent an impartial assessment of the thermoelectric stability of both dual-wall thermocouples and conventional thermocouples, which may provide assurance to potential users.

Keywords: thermocouples, MIMS, dual-wall, thermoelectric drift, type N, type K

(Some figures may appear in colour only in the online journal)

* Author to whom any correspondence should be addressed.



Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](https://creativecommons.org/licenses/by/4.0/). Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

1. Introduction

Base metal thermocouples are by far the most widely used temperature sensor in industry [1]. They consist of two thermoelements made of dissimilar base metal alloys connected at a tip, forming a measurement junction, with ceramic insulating material separating the two conductors. They are commonly sheathed to protect the thermocouple in harsh environments [2], such as from mechanical or thermal shock, and from chemical and atmospheric attack [3].

Over time, thermocouples demonstrate thermoelectric drift due to the effects of heating, thermal cycling, oxidation, and contamination [4]. This drift causes unknown temperature measurement errors, which in turn can severely affect the process for which the thermocouple is providing control. The effects of long term use at high temperature on the stability of base metal thermocouples have been studied since the 1940s [5], with further studies on nickel base thermocouples in particular in the 1960s [6, 7]. However, a lot of this early work only considered bare metal thermocouples, and so the findings may not be valid when considering the modern swaged mineral insulated, metal sheathed (MIMS) thermocouples.

The type K thermocouple is used very widely in industry and can be considered as the first successful low-cost thermocouple developed for high temperature use [2]. It is used as a general-purpose thermocouple, but suffers from steady, unpredictable drift above 500 °C which becomes worse as the temperature increases, becoming especially pronounced above 1000 °C. The type N thermocouple was developed as an improvement on the type K thermocouple, by making changes in the alloys that allow them to be used to higher temperatures, and make them more resistant to oxidation than the type K alloys [1, 8].

More recently, there has been a large number of studies on thermocouple drift in type K and type N MIMS thermocouples, which have shown overall that the change in Seebeck coefficient is heavily dependent on temperature [4].

Magnesium oxide is the most commonly used electrical insulation material because it resists oxidation and it is both chemically and physically stable at high temperatures [9]. However, it can absorb moisture and form an electrical shunt due to the resulting reduction in resistivity, which will affect the electromotive force (emf) readings of the thermocouple [2].

Sheath materials can also affect thermocouple performance. Best practice is to use an alloy closely related to the wire, such as Nicrosil or Nicrobell for type N and type K thermocouples, which perform better than stainless steel or Inconel.

One method to reduce drift is heat treatment of a MIMS type K or type N thermocouple before use. Annealing a thermocouple at a fixed temperature before it is put into service can reduce the amount of drift at high temperatures, although the optimal heat treatment in terms of temperature and length of time required depends on how the thermocouple will be used when in service [10, 11].

Another method is to decrease the chance of contamination, oxidation, or moisture ingress to the thermoelements when in

service. Normally this is done by selecting a sheath material best suited to the environment that the thermocouple will be used in.

Other ways of protecting the thermoelements are to increase thickness of the sheath, or to modify the internal structure of the MIMS thermocouple, by increasing the number of barriers between the environment and the thermoelements. One approach is to have a second layer of sheath material, which is the design investigated in this paper [12, 13]. Another design is to have additional layers of material surrounding the thermoelements themselves [14].

Thermocouples are also susceptible to influence from electromagnetic fields [15]. The effects of DC and AC magnetic fields on thermocouples are known and documented, especially in the temperature ranges below 0 °C and above 100 °C. They vary with the position of the thermocouple in the magnetic field and with the homogeneity of the field. The effect on the Seebeck coefficient is present along the entire length of the thermocouple wire exposed to the magnetic field [16] and is larger with thermocouples composed of ferromagnetic materials, such as iron, chromium and nickel [17].

There are multiple magnetic effects that can affect thermocouples. Electromagnetic effects cause changes in material properties such as magnetisation of the metal sensors or sheaths (the magneto-resistive effect), and they can also induce voltages in the thermocouple. Induction heating can cause an increase in temperature, due to changes in magnetic fields caused by eddy currents in metallic materials. Mechanical effects, such as the magnetic force induced by a magnetic field, can cause displacement of the thermocouple, and potentially change the heat transfer properties [16].

The errors of thermocouples regularly exposed to magnetic fields are around ± 1 °C but can be decreased down to 0.1 °C [16]. If even better accuracy is required, there are two possibilities. The first is to use a type of thermometer that is insensitive to magnetic fields up to the maximum strength likely to be encountered, such as a fibre-optic thermometer or a pyrometer. The other is to apply a correction of the thermocouple reading. Accurate corrections are only possible when the magnetic field strength is known or measured which is difficult when the field is anisotropic or non-constant [18].

This investigation compares the performance of conventional MIMS thermocouples and a new design of MIMS thermocouple with two protective sheaths, the so-called dual-wall thermocouples. All thermocouples were supplied by the University of Cambridge and CCPI Europe Ltd. The dual wall thermocouples have an additional inner sheath between the outer sheath and the thermoelements [19] which can be seen in figure 1. The purpose of the secondary sheath is to reduce the transfer of materials from the outer sheath to the thermoelements, with the aim of reducing the thermocouple drift. Currently the only information available on calibration drift performance is that from the manufacturers themselves, which is of only very limited use to end-users who are more likely to need an impartial assessment.

To provide more confidence for end users and regulatory bodies that the thermocouple represents an improvement, and

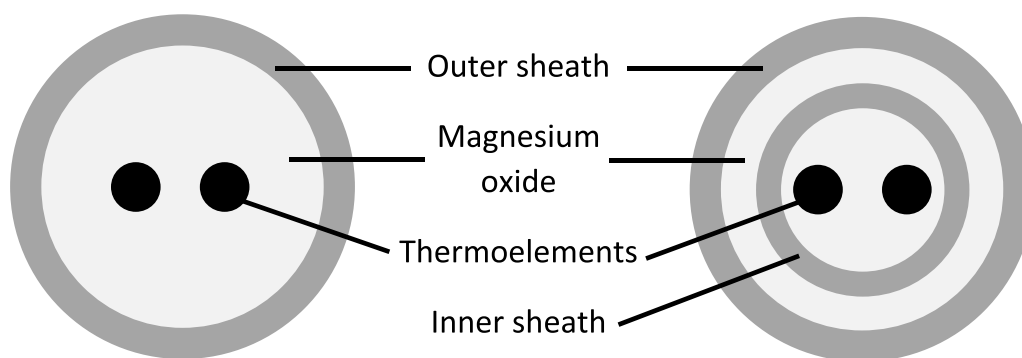


Figure 1. A cross section of a conventional MIMS thermocouple (left) alongside a dual-wall MIMS thermocouple (right).

by how much, the six NMIs carried out a systematic programme of work to objectively compare the drift performance of the new dual-walled thermocouples and conventional thermocouples. The performance is investigated with respect to high temperatures (both in the steady state, and under thermal cycling), and to high magnetic fields.

This will benefit the industrial thermometry community by providing confidence in the performance of the novel temperature sensors as compared with equivalent conventional ones, with the potential benefits being more stable and reliable temperature measurements.

In section 2 the measurements are described. The results of the type N thermocouples are provided and discussed in section 3.2. In section 3.3, the results of the type K thermocouples are shown and discussed, and an overall summary of the drift tests is discussed in section 3.4. In section 3.5, the electromagnetic field results are shown and discussed. Conclusions are drawn in section 4.

2. Measurements

2.1. Drift investigation

The measurement protocol consisted of five main parts: thermoelectric homogeneity scans at 200 °C of all MIMS thermocouples before the start of the test, calibration at the Fe–C fixed point in argon (1153 °C) [20], and then the drift tests in air, followed by another calibration at the melting point of the Fe–C fixed point, and a final homogeneity scan. Three of the labs performed isothermal drift tests, where the thermocouples were held at 1200 °C, and the other three performed thermal cycling drift tests where the temperature was repeatedly ramped up and down between 300 °C and 1150 °C. The temperature profiles of the NMIs' furnaces used for the drift tests and for the calibrations at Fe–C fixed points were optimised and measured to ensure that they were as similar as possible. This was done to ensure that the Fe–C calibrations pertained to the same section of thermocouple that was subjected to the drift tests, where possible. The full set of profiles can be found in appendix A.

As part of the measurement protocol, each lab was provided with four type N thermocouples (two conventional and two

dual-wall) and four type K thermocouples (two conventional and two dual-wall). All thermocouples had an outer sheath diameter of 3 mm in diameter. The measurement protocol was carried out twice, once for the type N thermocouples and once for the type K thermocouples and was identical each time. The full protocol is described in detail in appendix B. The equipment used for the tests varied between the laboratories and is described in appendix C. The lengths of the thermocouple used are described in appendix D.

2.2. Electromagnetic field investigation

For the electromagnetic field tests, eight MIMS thermocouples were tested at the University of Ljubljana: four type N thermocouples (two conventional and two dual-wall) and four type K thermocouples (two conventional and two dual-wall). The thermocouples were tested at five different temperatures: –196 °C, 0 °C, 125 °C, 250 °C, 500 °C.

The coil constants of the coils used were measured with a Hall magnetometer. In all cases, the temperatures indicated by the thermocouples were logged on a PC via a thermally insulated Batemika UT-ONE S12 12 channel thermometer readout.

At temperatures of –196 °C (liquid nitrogen) and 0 °C (ice point), the test thermocouples were inserted in a small Dewar flask containing liquid nitrogen or an ice-water mix. The dewar was then inserted in a smaller round coil with the coil constant of 2.22 mT A^{–1}. The AC current through the coil was 6.75 A, which generated a magnetic flux density of 15 mT.

At temperatures above 0 °C, the test thermocouples were inserted into a small custom-made laboratory furnace. The furnace heaters were connected to a DC power supply, where a power of approximately 200 W was required to maintain a stable temperature of approximately 500 °C. In this set up, a larger square coil with the coil constant of 0.75 mT A^{–1} was used. The current through the coil was 4 A, which generated a magnetic flux density of 3 mT.

In total, the measurement at each temperature was performed over a period of 4–6 h, depending on the temperature and how long it took to reach equilibrium. When the

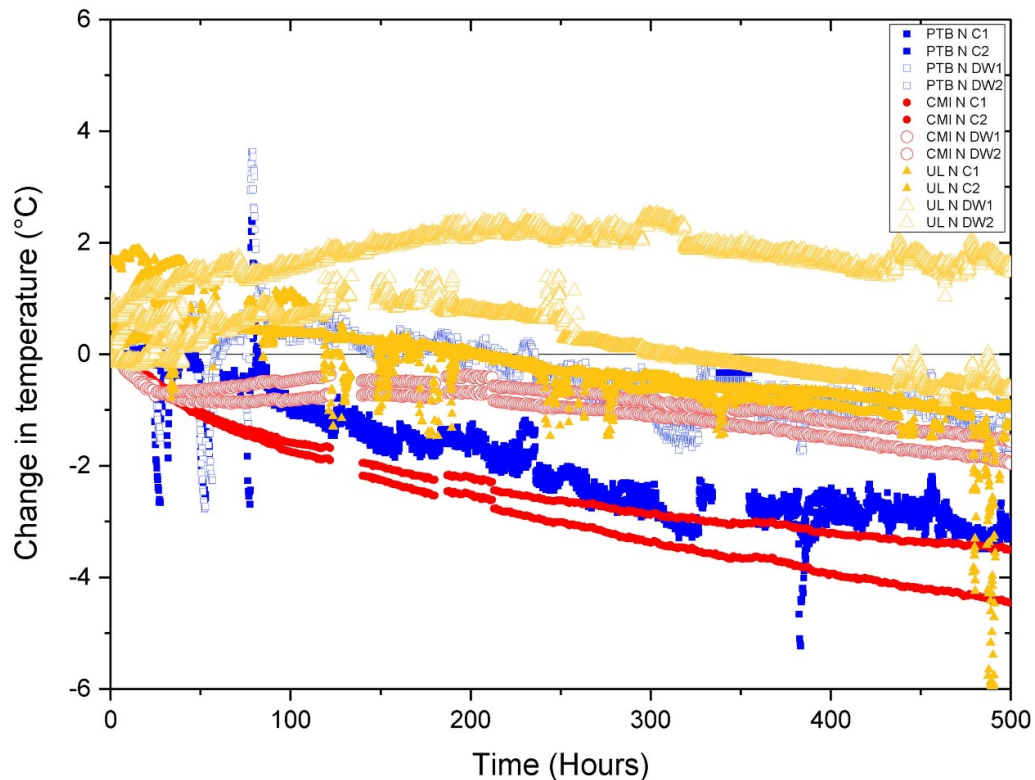


Figure 2. Change in indicated temperature from the initial value as a function of time for 12 type N thermocouples at three different NMIs (PTB, CMI, UL) during the isothermal tests.

temperature was stable, the electric and magnetic field was activated for 5 min. The difference between stable temperature and temperature after the exposure to the field was taken as indication of the effect. The measurements were repeated a minimum of three times, in order to estimate the reproducibility and confirm the results.

3. Results and discussion

3.1. Drift investigation

The drift data for all 12 thermocouples in the isothermal tests has been adjusted with respect to a reference thermocouple, in order to remove the effect of furnace temperature variations, or other noise measured by the thermocouples. The measurements at the Fe–C fixed point are presented as measured. For the naming convention of the thermocouples, ‘C’ denotes conventional MIMS thermocouples; ‘DW’ denotes dual-wall MIMS thermocouples.

Some excessive electrical noise has been removed from the datasets where possible. The approach was taken that in the cases of outlying, anomalous or otherwise data, the data was presented in the relevant figure, but not included in the final analysis.

The thermoelectric inhomogeneity is defined as the peak-to-peak variation in temperature along the length of the thermocouple as it was scanned in the oil or salt baths. The initial

thermoelectric inhomogeneity before the tests of all thermocouples tested was 1 °C or less.

3.2. Type N

3.2.1. Isothermal drift tests. Overall negative drift was observed for 11 of the 12 type N thermocouples, with the exception of UL N DW1, which showed a drift of approximately +1.0 °C (figure 2). This negative drift is also reflected in the Fe–C calibrations performed before and after the isothermal drift tests at PTB and UL, which also show a decrease in the emf measured at the Fe–C point corresponding to a negative drift (figure 3). The average drift of the conventional type N thermocouples was -2.7 °C over 500 h with a standard deviation of 1.3 °C, and the average drift of the dual-wall thermocouples was -0.9 °C over the same period with a standard deviation of 1.2 °C.

The large differences between the measurements at the Fe–C fixed point before and after isothermal treatment at 1200 °C for the type N thermocouples at PTB are most likely due to changes in the type N thermocouples themselves, which have altered the Seebeck coefficient. This issue was observed also in the thermocouples’ homogeneity scans, before and after the isothermal test. By comparing the thermoelectric voltage differences at 200 °C and at maximum installation depth (table 1), it is apparent that the measured thermoelectric voltages are lower by a temperature equivalent of approximately 10 °C. The ratio of the emfs at 1153 °C to

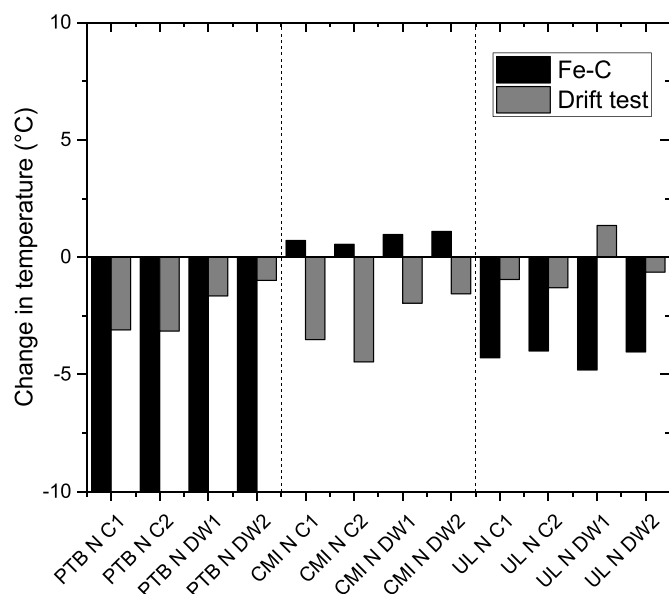


Figure 3. Comparison of the apparent temperature drift for the two different methods of measuring it: the *in-situ* drift from the isothermal drift tests (the change in apparent temperature when corrected against the reference thermocouple) and the calibrations at the Fe–C point. Note that the measurements for the Fe–C calibrations at PTB were -85.3°C , -80.2°C , -57.5°C and -60.4°C , and so have been left off this figure for clarity.

Table 1. Emf and temperature differences (after–before) during homogeneity check at 200°C at PTB.

Before and after isothermal drift tests 1200°C	CC1	CC2	DW1	DW2
$\Delta\text{emf at } 200^{\circ}\text{C}/\mu\text{V}$	333.2	336.0	306.2	279.4
$\Delta T \text{ at } 200^{\circ}\text{C}/\text{K}$	10.1	10.2	9.3	8.5

200°C ($42\,170\,\mu\text{V}/5880\,\mu\text{V}$) is approximately 7.2. According to generally accepted methods for extrapolating thermoelectric inhomogeneities from the oil bath temperature (where the inhomogeneity was measured) to the Fe–C melting temperature [21], this broadly explains the differences at the Fe–C point before and after the isothermal drift tests. Since the immersion depth of the type N thermocouples during the isothermal drift tests was significantly larger than during calibration at the Fe–C fixed point, the sections of wire that were most significantly degraded during the isothermal test at 1200°C were situated in the zone with highest temperature gradient of the Fe–C furnace, which probably caused the large differences of -60°C to -90°C and the uncertainties associated to these determinations are also high.

The Fe–C calibrations performed at CMI show an increase in the emf measured at the Fe–C point (positive drift), whereas the *in-situ* drift measurements during the isothermal tests show a decrease in the emf (negative drift).

The homogeneity after testing of the dual-walled type N thermocouples compared to the conventional type N thermocouples varied depending on the NMI, as described in figure 4.

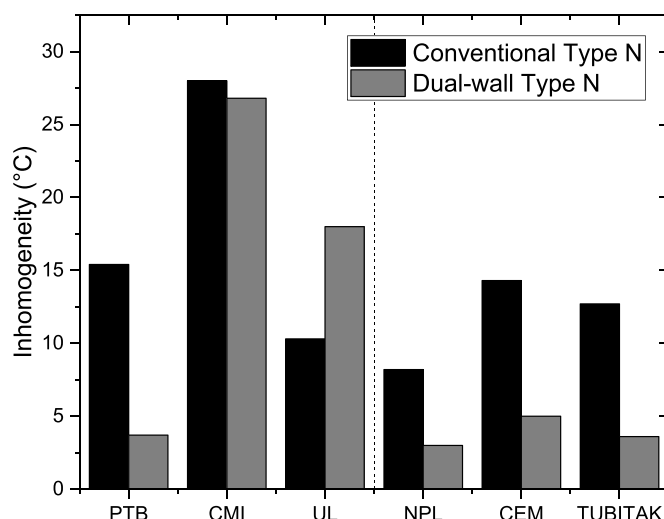


Figure 4. Average thermoelectric inhomogeneity for each type N thermocouple design as measured at each NMI after drift tests were complete.

This is most likely due to the fact that the thermocouples were tested in different furnaces with different temperature gradients, resulting in different inhomogeneities in the tested thermocouples. For PTB and CMI, the conventional thermocouples show larger inhomogeneities than the dual-wall thermocouples, but the opposite is the case for UL.

This is thought to be caused by the same issue that affected the PTB thermocouples, where the different gradients in the different furnaces mean that large inhomogeneities form at different points along the thermocouple wires, and these cause large temperature measurement variations when the thermocouples are moved into different temperature gradients. It is due to this movement between different temperature gradients that the drift according to the Fe–C measurements is less reliable in this case.

3.2.2. Thermal cycling. Of the dual-wall type N thermocouples tested at NPL, CEM and TUBITAK, three showed a positive drift, and three showed a negative drift, which was shown in both during the thermal cycling drift tests (figure 5) and from the Fe–C calibrations (figure 6). All six conventional thermocouples drifted negatively. It is unclear why there was a difference between the dual wall type N thermocouples. However, the dual-wall type N thermocouples in the thermal cycling tests showed less drift than the conventional thermocouples.

The drift tests show that for the thermal cycling tests, the average *in-situ* drift (for the three involved NMIs) of the conventional type N thermocouples was -1.7°C with a standard deviation of 0.6°C . The average *in-situ* drift of the dual-wall thermocouples was -0.3°C with a standard deviation of 0.9°C . This is reflected in the Fe–C calibrations, which showed an average change in the measured emf of -1.2°C for the conventional type N thermocouples and $+0.9^{\circ}\text{C}$ for the dual-wall thermocouples.

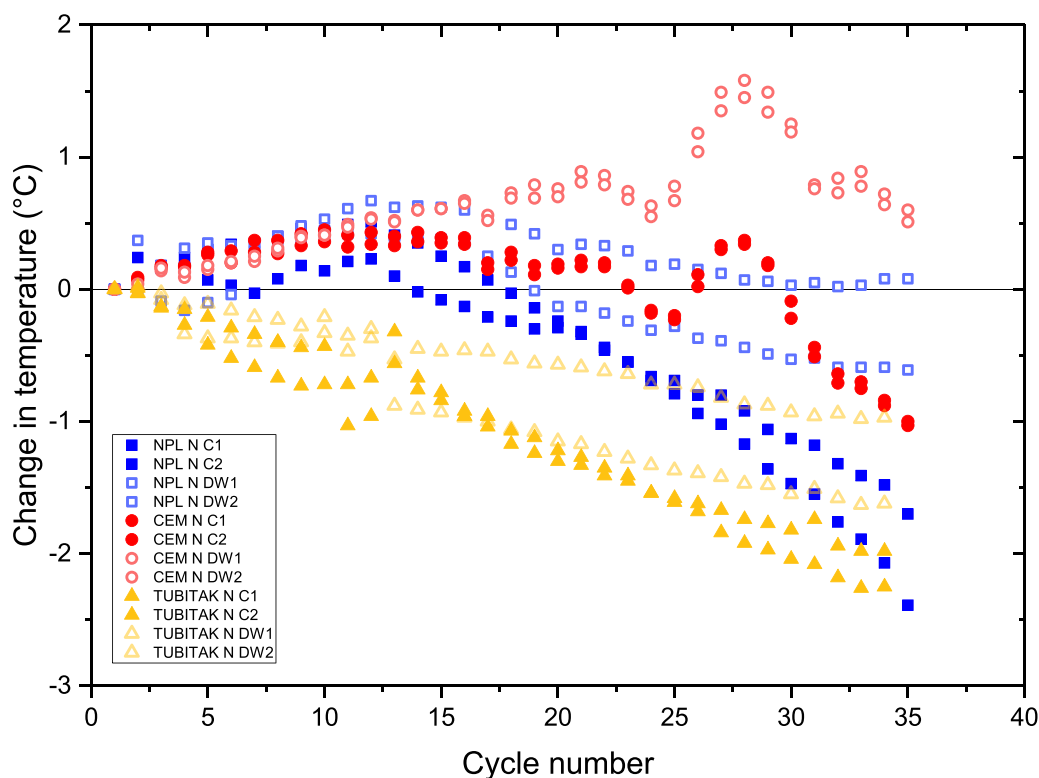


Figure 5. Change in temperature from initial recorded temperature for 12 type N thermocouples at three different labs (NPL, CEM, TUBITAK) during the thermal cycling tests.

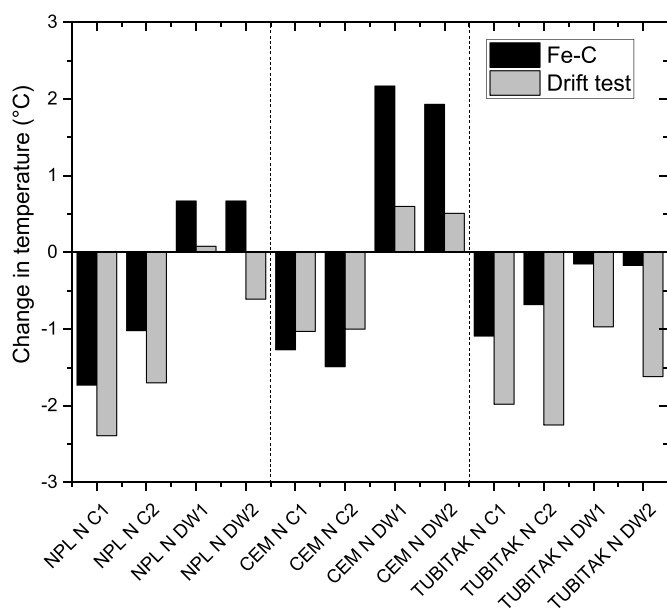


Figure 6. Comparison of the apparent temperature drift for the two different methods of measuring it: the *in-situ* drift from the type N thermal cycling drift tests (the change in apparent temperature when corrected against the reference thermocouple) and the calibrations at the Fe–C fixed point.

In addition to experiencing a smaller drift, the inhomogeneities seen in the dual-wall thermocouples were smaller than those seen in the conventional thermocouples (figure 4). After the thermal cycling tests, the conventional thermocouples had

an average inhomogeneity of 11.8 °C with a standard deviation of 3.1 °C, whereas the dual-wall thermocouple average inhomogeneity was 3.9 °C with a standard deviation of 1.3 °C. This means that when the thermocouples were moved into different temperature gradients, the measurement variations caused by inhomogeneity is smaller for the dual-wall thermocouples and consequently, the associated uncertainty to their measurements is also lower than for conventional thermocouples.

3.3. Type K

3.3.1. Isothermal drift tests. For type K thermocouples, the isothermal drift tests showed that 10 out of 12 had drifted negatively by the end of the test, with two showing an overall positive drift (figure 7). However, when considering the thermocouples between 50 and 500 h at 1200 °C, all 12 thermocouples showed negative drift. Comparison between the type K dual-wall and conventional thermocouples in the isothermal drift tests shows that across PTB, CMI and UL, the average drift of the conventional thermocouples was −2.3 °C with a standard deviation of 0.6 °C. The average drift of the dual-wall thermocouples was −1.9 °C with a standard deviation of 0.6 °C.

Similarly to the type N thermocouples, the Fe–C calibrations performed on the type K thermocouples, before and after the isothermal drift tests at PTB and UL, show a decrease in the emf measured at the Fe–C point before and after the tests (figure 8).

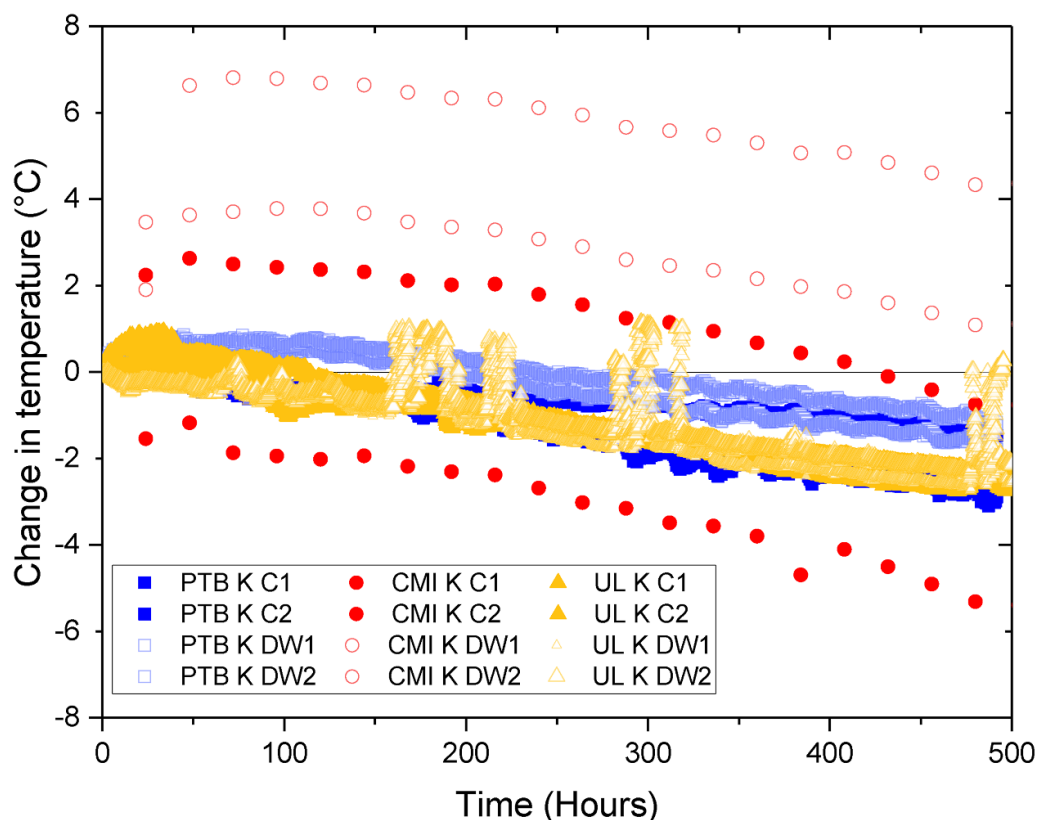


Figure 7. Change in temperature from initial recorded temperature for 12 type K thermocouples at three different NMIs during the isothermal tests. It can be seen here the anomalous nature of the CMI measurements.

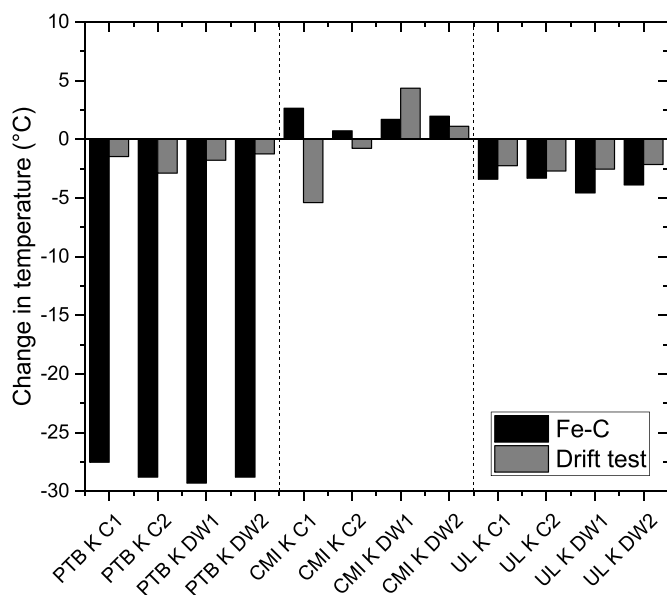


Figure 8. Comparison of the apparent temperature drift for the two different methods of measuring it: the drift from the type K isothermal drift tests (the change in apparent temperature when corrected against the reference thermocouple) and the calibrations at the Fe-C point.

At PTB, there was a large difference in the magnitude of drift of the type K thermocouples measured when comparing the Fe-C point and the isothermal drift measurements.

The differences measured at the Fe-C fixed point before and after the isothermal drift tests were smaller than for the type N thermocouples, but still of the order of almost -30 °C. Here, only some of the areas previously exposed to 1200 °C were in the temperature gradient of the Fe-C furnace. Additionally, the two temperature gradients of the furnaces used in the Fe-C fixed point calibration and the drift tests are different, so a direct comparison of the emfs at maximum insertion during the homogeneity tests are less useful. Nevertheless, the inhomogeneities determined from the measured immersion profiles at 200 °C after the isothermal drift tests at 1200 °C were approximately 15 °C, which also indicates a degradation effect on the Seebeck coefficient during this process, similar to that observed for the type N thermocouples.

As can be seen from figures 7 and 8, the CMI results are anomalous compared to the rest of the data. A difference between the drift measurements and the Fe-C measurements could be caused the same issues as PTB, but the large increase for three of the thermocouples and large decrease for another are unexplained, and as a result, these values are not included in the average drift calculations. However, the slope of the drift after first 50 h shows a similar level of drift when compared to PTB and UL.

For the isothermal tests, the thermoelectric inhomogeneity was greater for the dual-wall type K thermocouples than for the conventional type K thermocouples (figure 9), but it is unclear why this might be.

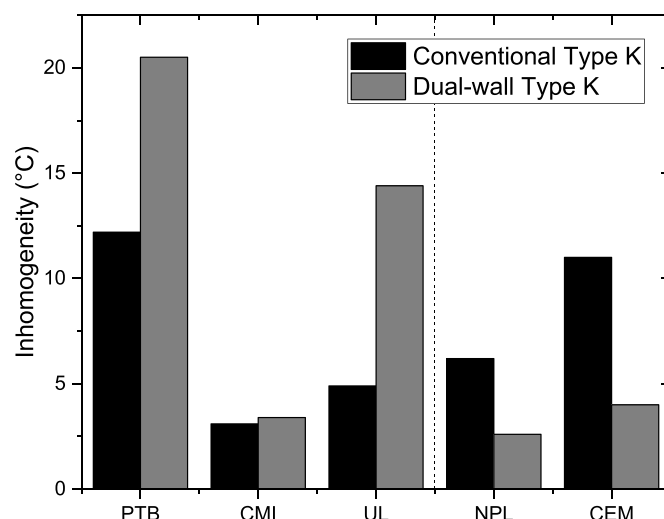


Figure 9. Average inhomogeneity for each type K thermocouple design at each lab after drift tests were complete, where PTB, CMI and UL performed isothermal drift tests, and NPL, CEM and TUBITAK performed thermal cycling tests. Final homogeneity scans at TUBITAK were not completed.

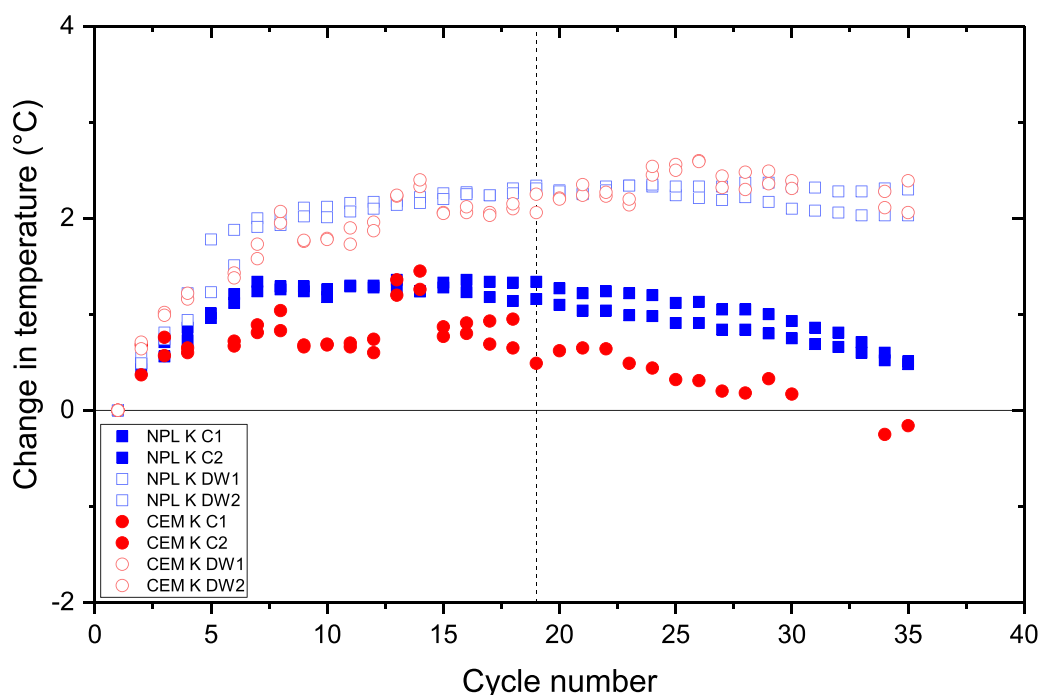


Figure 10. Change in temperature from initial recorded temperature for eight type K thermocouples at NPL and CEM during the thermal cycling tests. The dotted line at 18 cycles marks the point where CEM K C1 failed.

3.3.2. Thermal cycling. For the thermal cycling measurements on the type K thermocouples, the dual-wall thermocouples showed a larger magnitude of drift, in both the drift tests and in the Fe–C calibrations performed before and after. However, the direction of the drift was not universal, and two conventional type K thermocouples (one at CEM and one at TUBITAK) failed during the drift tests, so their results have been removed from any average values calculated.

The type K thermocouples tested at NPL and CEM drifted positively, with an average of $+0.3$ °C for the conventional

thermocouples with a standard deviation of 0.4 °C, and $+2.2$ °C for the dual wall thermocouples with a standard deviation of 0.2 °C (figure 10). Figure 11 shows that the Fe–C measurements confirm that the thermocouples drifted positively, with the dual-wall thermocouples showing a greater drift.

During the tests at TUBITAK, the control thermocouple for the furnace and one of the heating elements failed, and during repairs, the thermocouples were moved within the furnace, causing the abrupt change after 16 cycles (figure 12). Because

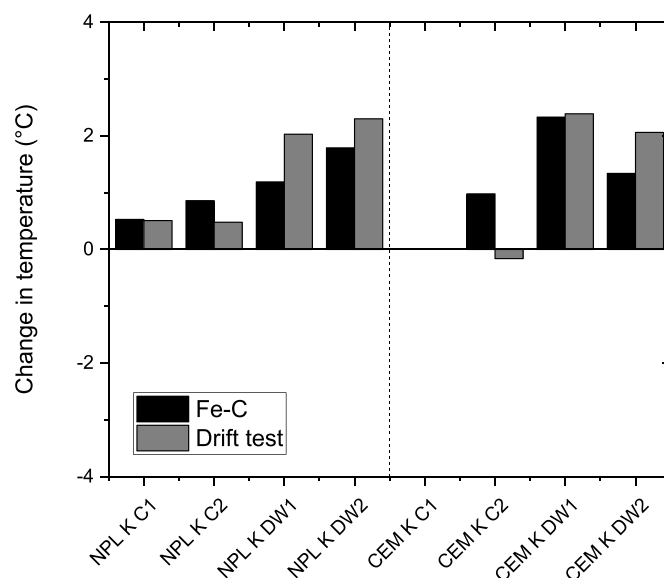


Figure 11. Comparison of the apparent temperature drift for the two different methods of measuring it: the *in-situ* drift seen during the type K thermal cycling drift tests (the change in apparent temperature when corrected against the reference thermocouple) and seen during the calibrations at the Fe–C point. Final Fe–C calibrations at TUBITAK were not completed.

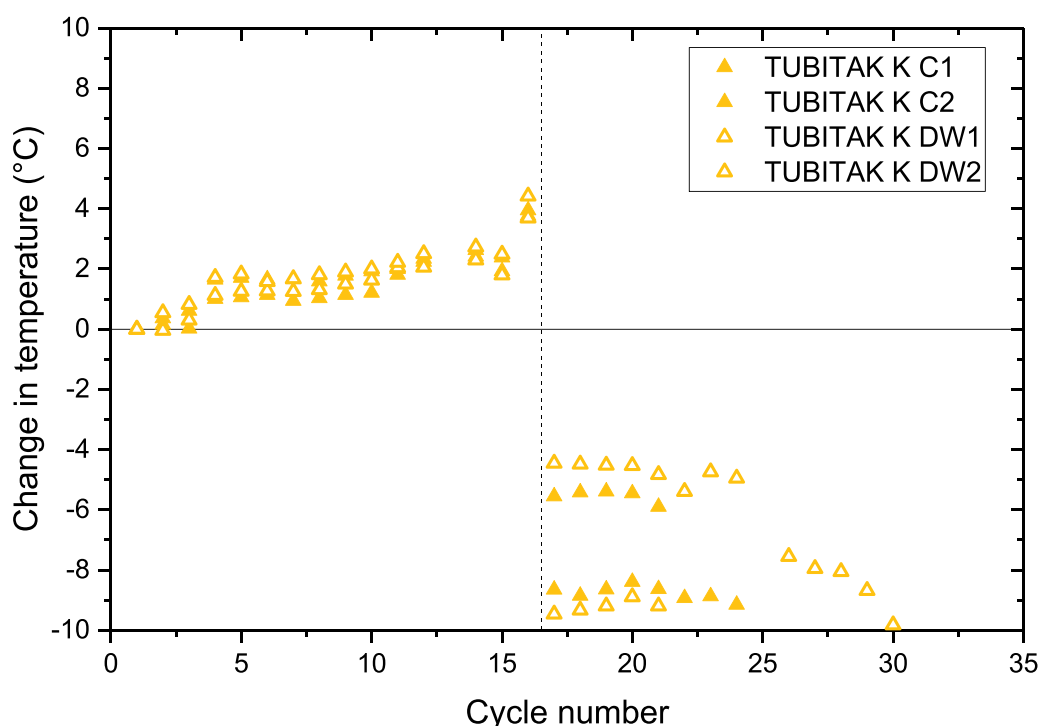


Figure 12. Change in temperature from initial recorded temperature for four type K thermocouples at TUBITAK during the thermal cycling tests. The dotted line after 16 cycles marks the point where the furnace was repaired, and the thermocouple position or the temperature profile of the furnace changed.

of this, the drift values for the four type K thermocouples at TUBITAK are not used to calculate the average drift for the thermal cycling tests.

Before the furnace breakage, the TUBITAK thermocouples were all showing positive *in-situ* drift (figure 12), as were all other type K thermocouples in the thermal cycling tests (figure 10). This could be due to the thermocouples in the thermal cycling tests spending more time in the

temperature range 300 °C–650 °C than the isothermal drift test thermocouples, which would be expected to cause an overall positive drift for type K thermocouples [19].

After the thermal cycling tests, the thermoelectric inhomogeneity was greater for the conventional type K thermocouples than for the dual-wall type K thermocouples (figure 9). This is the same as what was seen in the thermal cycling tests for the type N thermocouples, but different to what was seen for type

Table 2. The average influence of the AC magnetic field on the measured temperature of the test thermocouples after a 5 min exposure.

Temperature/°C	Magnetic field/mT	Change in measured temperature/°C							
		NC1	NC2	NDW1	NDW2	KC1	KC2	KDW1	KDW2
−196	15	0.05	0.05	0	0	0	0	0.05	0.10
0	15	0	0	0	0	0	0.03	0.03	0.03
125	3	0	0	0.10	0.20	0.10	0.05	0.15	0.30
250	3	0	0	0.04	0.08	0	0.04	0.04	0.10
500	3	0	0	0	0	0	0	0	0.02

K thermocouples that were subjected to the isothermal drift tests.

3.4. Overall drift test analysis

The thermocouples in the isothermal drift tests tend to have an overall negative *in-situ* drift. This is in agreement with previous investigations, where both type N and type K thermocouples have a decrease in the Seebeck coefficient above 1100 °C [22]. For the thermal cycling tests, the conventional type N thermocouples had a negative drift, whereas some of the dual-wall thermocouples had a positive drift. The dual-wall nature of the thermocouples may have contributed to this. For the type K thermocouples in the thermal cycling tests, the majority showed a positive drift.

For both type N and type K thermocouples, the localised changes in the Seebeck coefficients (as demonstrated by the homogeneity tests) are the most likely causes of large differences in the thermoelectric voltages measured at the Fe–C fixed point before and after the drift tests, which are associated with different temperature profiles in the furnaces used. During the *in-situ* comparison, where the thermocouple position is unchanged with respect to the temperature gradient, good thermoelectric stability can be seen. However, this was only maintained with unchanged external measuring conditions. Once the thermocouple is moved into a different temperature gradient, as it was during the tests at PTB, the apparent temperature drift can be very different. Because of these differences, the Fe–C measurements were not considered when estimating the average drift values.

3.5. Electrical and magnetic fields

The influence of temperature on the extent to which an applied magnetic field influences the measured temperature was investigated. The largest magnetic field influence was measured at 125 °C for six of the eight thermocouples tested (table 2 and figure 13), so additional tests were performed at this temperature to assess the time dependence. It was found that there was no AC signal effect on the recording equipment or on the power supply.

Based on the measurements (table 2), the magnetic field appears to cause a rise in the measured temperature which is higher with dual wall thermocouples than conventional thermocouples, with the effect being more pronounced for the type K thermocouples than for the type N thermocouples. However,

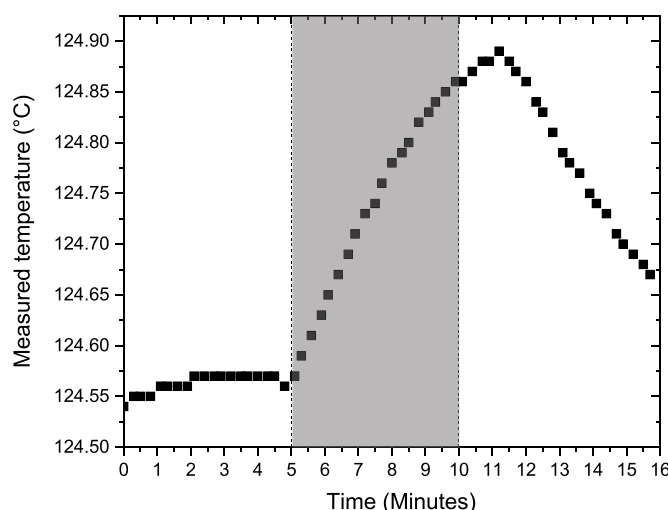


Figure 13. Measured temperature as a function of time for a thermocouple at 125 °C during exposure to an AC magnetic field. The shaded area between 5 and 10 min indicate where the magnetic field was activated and subsequently deactivated.

the reason for this is unclear and further investigation is needed in order to confirm and explain the potential effect.

4. Conclusion

For the drift measurements, 48 thermocouples were tested at six different NMIs. At each NMI, four conventional and four dual-walled thermocouples underwent a homogeneity scan, were calibrated at the Fe–C fixed point, and then subjected to either 500 h at 1200 °C, or thermally cycled between 300 °C and 1150 °C. They were then calibrated again at the Fe–C fixed point before undergoing a final homogeneity scan. Eight additional thermocouples underwent tests in electromagnetic fields.

The average drift of the thermocouples is summarised in table 3. For the type N thermocouples, the dual-wall thermocouples showed a significantly reduced thermoelectric *in-situ* drift compared to the conventional thermocouples. Within the isothermal tests, the average drift of the conventional thermocouples was −2.7 °C with a standard deviation of 1.3 °C, and −0.9 °C with a standard deviation of 1.2 °C for the dual wall thermocouples. For the thermal cycling tests, the average drift of the conventional thermocouples was −1.7 °C with a standard deviation of 0.6 °C, and −0.3 °C with a standard deviation of 0.9 °C for the dual wall thermocouples.

Table 3. A summary of the average drift rates and standard deviation for each thermocouple design in each test.

Thermocouple type	Type of test	Thermocouple design	Average drift/ $^{\circ}\text{C}$	Standard deviation/ $^{\circ}\text{C}$
N	Isothermal	Conventional	−2.7	1.3
		Dual-wall	−0.9	1.2
	Thermal Cycling	Conventional	−1.7	0.6
		Dual-wall	−0.3	0.9
K	Isothermal	Conventional	−2.3	0.6
		Dual-wall	−1.9	0.6
	Thermal Cycling	Conventional	+0.3	0.4
		Dual-wall	+2.2	0.2

For the type K thermocouples, in the isothermal tests, the overall drift of the conventional thermocouples was -2.3°C with a standard deviation of 0.6°C , and the average drift of the dual-wall thermocouples was -1.9°C with a standard deviation of 0.6°C . The dual-wall thermocouples showed an increased thermoelectric *in-situ* drift compared to the conventional thermocouples for the thermal cycling tests, that is, $+0.3^{\circ}\text{C}$ for the conventional thermocouples with a standard deviation of 0.4°C , and $+2.2^{\circ}\text{C}$ for the dual wall thermocouples with a standard deviation of 0.2°C . Considering these values, the thermoelectric stability did not vary significantly between the conventional and dual-wall type K thermocouples during the isothermal tests. During the thermal cycling tests, the dual wall thermocouples showed greater *in-situ* drift than the conventional thermocouples. These were confirmed by calibrations at the Fe–C point, but only when the temperature gradient was the same in both set ups.

As would be expected for MIMS thermocouples, significant thermoelectric inhomogeneity was seen across all thermocouples after testing, which caused large temperature measurement errors when the thermocouples were moved into a different temperature gradient. Overall, the dual-wall type N thermocouples were more homogeneous after the testing, and there was no clear difference between the dual-wall and conventional type K thermocouples.

All 12 dual-wall thermocouples completed the measurement protocol, and 2 out of 12 conventional thermocouples failed during the thermal cycling testing, both of these being type K.

In the presence of a magnetic field, it appeared that the dual-wall thermocouples were affected more than the conventional thermocouples, with the type K dual-wall thermocouples showing the greatest deviation. However, the reasons behind this are not known, and further work is needed to establish the reasons for this.

The reduced amount of drift seen in the dual wall type N thermocouples will mean that the thermocouples will stay within a given tolerance for a longer period of time, therefore reducing the measurement uncertainty, and allowing extended recalibration intervals.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

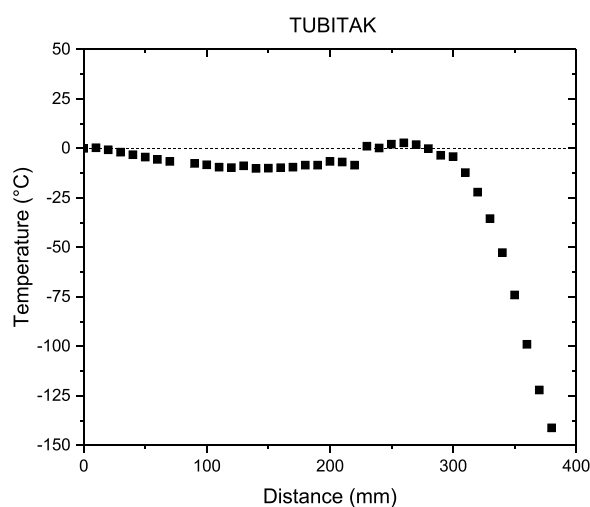
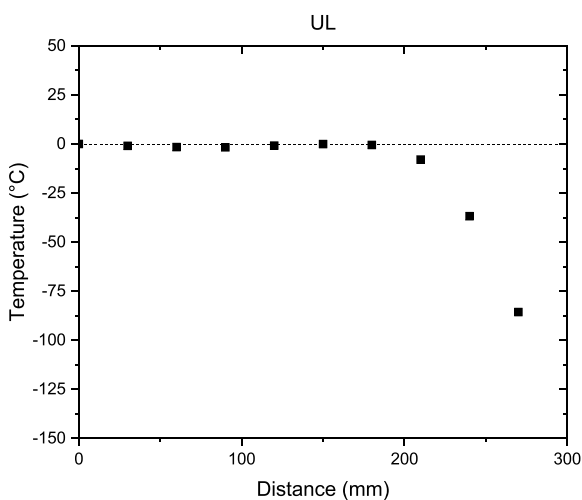
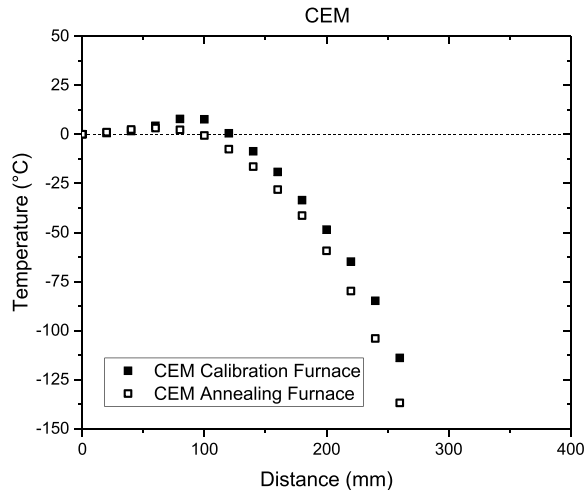
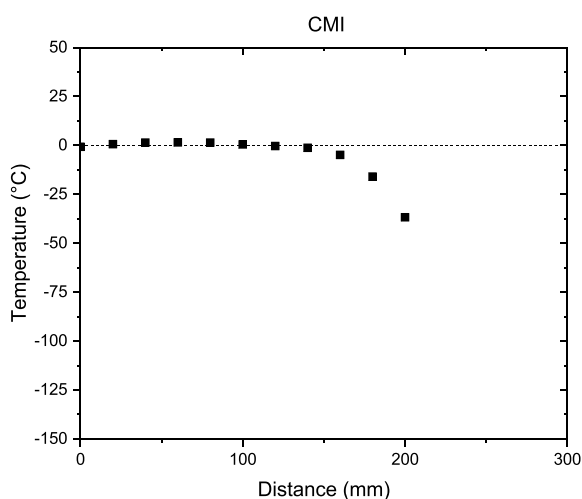
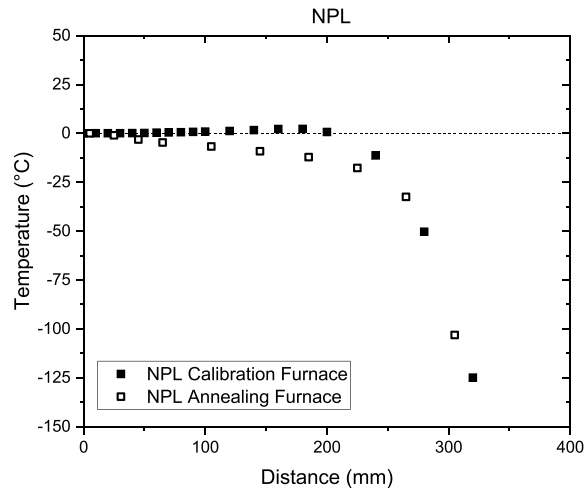
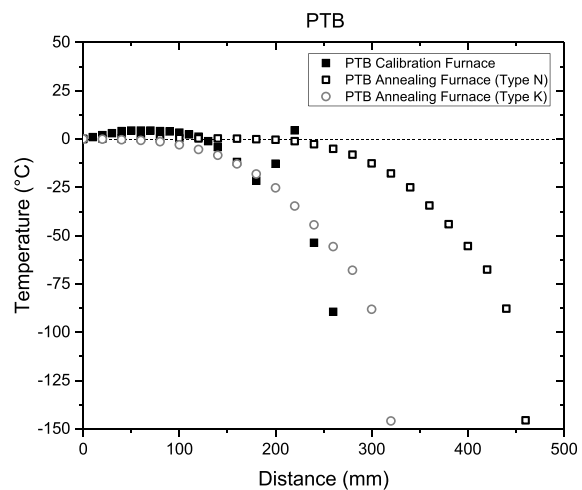
Acknowledgments

The authors thank Trevor Ford, Phill Williams and Peter Cowley (CCPI Europe Ltd) for supplying the MIMS thermocouples and for their other contributions.

This project (17IND04 ‘EMPRESS 2’), has received funding from the European Metrology Programme for Innovation and Research (EMPIR) programme jointly funded by the EMPIR participating countries within EURAMET and the European Union.

Appendix A

Furnace profiles for each of the six NMIs. Only one furnace profile shown for labs which used the same furnace for both.



Appendix B

Measurement protocol

- (a) Measurement of the gradient of the drift test furnace, where the hottest region of the furnace (where the thermocouple tips were positioned) at 1200 °C for the isothermal tests, and 1150 °C for the thermal cycling tests
- (b) Measurement of the temperature gradient of the Fe–C calibration furnace
- (c) Thermoelectric homogeneity test for each MIMS thermocouple, undertaken in a stirred oil bath at 200 °C
- (d) Calibration of the dual wall and conventional thermocouples before the drift test using an Fe–C cell, with only one transition through the melting-freezing sequence to minimise the time at high temperature before the drift test. All calibrations at the Fe–C fixed point were carried out in an argon atmosphere
- (e) Drift tests
 - 1. NPL, CEM and TUBITAK undertook thermal cycling tests in air, as follows:
 - (i) The thermocouples (both dual wall and conventional) were immersed in the furnace at ambient temperature along with a Pt based reference thermocouple, with the same immersion depth for all sensors
 - (ii) The furnace temperature was increased to 300 °C
 - (iii) 35 temperature cycles were executed; a cycle is described as follows:
 - (A) Temperature increased at 1.5 °C min⁻¹ from 300 °C to 1150 °C
 - (B) Temperature held at 1150 °C for 4 h
 - (C) Temperature decreased at 2 °C min⁻¹ from 1150 °C to 300 °C
 - (D) Temperature held at 300 °C for 15 min
 - (iv) At the end of the cycles, the temperature was decreased to ambient temperature
 - 2. UL, CMI and PTB undertook isothermal tests in air, as follows:
 - (i) The thermocouples (both dual wall and conventional) were immersed in the furnace at ambient temperature along with a noble metal reference thermocouple, with the same immersion depth for all sensors
 - (ii) The furnace temperature was increased to 1200 °C
 - (iii) The furnace temperature was held at 1200 °C for 500 h
 - (iv) The furnace temperature was decreased to ambient temperature
- (f) Calibration of the dual wall and conventional thermocouples using an Fe–C fixed point
- (g) Final thermoelectric homogeneity tests of each MIMS thermocouple

Appendix C

Equipment used by each laboratory.

NMI	Homogeneity scan	Fe–C calibration	Drift tests	Reference junction
NPL	Keithley 2182A voltmeter Fluke oil bath	Keithley 2182A voltmeter Elite 1600 °C 3 heater zone furnace	Keithley 2182A voltmeter and Keithley 7001 switch Elite 4 heater zone annealing furnace	Fluke automatic zero-point calibrator
CEM	Keithley 2182A Heto Oil bath	HP 3458A CEM 1550 vertical	HP 3458A CEM 1550 vertical	Water bath with water temperature measurements for thermal cycling test. Crushed ice point for measurements at Fe–C fixed point and homogeneity tests Labo Company liquid bath
TUBITAK	1586A SUPER-DAQ Precision Temperature Scanner Labo Company liquid bath	1586A SUPER-DAQ Precision Temperature Scanner Magma Therm Isothermal furnace	1586A SUPER-DAQ Precision Temperature Scanner Magma Therm Isothermal furnace	
PTB	Keithley 2182 voltmeter Fluke 6055 salt bath	Keithley 2182 voltmeter HTF-Reetz furnace	Prema 5017 Multimeter and Prema 2080 Scanner, 10-zone furnace	Crushed ice point for type N Fluke 9170 block calibrator for type K
CMI	Fluke 8508A multimeter oil bath	Datron 1081 multimeter Clasic 3 zone furnace	Fluke 8508A multimeter Elsklo horizontal furnace	Crushed ice point
UL	Batemika UT-ONE S12 thermometer readout Kambič Metrology high temperature oil bath	Agilent 3458A multimeter Kambič Metrology UHTCC furnace	Batemika UT-ONE S12 thermometer readout Kambič Metrology UHTCC furnace	Batemika UT-ONE S12 thermometer readout or ice point

Appendix D

Table describing the length of the thermocouples used at each laboratory.

NMI	Length (mm)
PTB	700
CMI	510
UL	500
NPL	700
CEM	500
TUBITAK	800

ORCID iDs

D J L Tucker  <https://orcid.org/0000-0002-4173-3433>
 F Edler  <https://orcid.org/0000-0002-0413-1337>
 C Garcia-Izquierdo  <https://orcid.org/0000-0001-8183-1399>

References

- [1] Quinn T J 1990 *Temperature* (London: Academic Press Ltd) pp 309–11
- [2] Nicholas J V and White D R 2001 *Traceable Temperatures* (Chichester: Wiley) pp 307–17
- [3] Michalski L, Eckersdorf K and McGhee J 1991 *Temperature Measurement* (Chichester: Wiley) p 61
- [4] Machin J, Tucker D J L and Pearce J V 2021 A comprehensive survey of reported thermocouple drift rates since 1972 *Int. J. Thermophys.* **42** 139
- [5] Dahl A I 1940 Stability of base-metal thermocouples in air from 800 °F to 2200 °F *J. Res. Natl Bur. Stand.* **24** 263–89
- [6] Potts J F Jr and McElroy D L 1962 The effects of cold working, heat treatment, and oxidation on the thermal emf of nickel-base thermoelements *Temp. Meas. Control Sci. Ind.* **3** 243
- [7] Cadwell F R 1962 Thermocouple materials *Temperature Its Measurement and Control in Science and Industry* vol 3 (New York: Reinhold) pp 81–134
- [8] Burley N A, Powell R L, Burns G W and Scroger G M 1978 *The Nicrosil versus Nisil Thermocouple: Properties and Thermoelectric Reference Data* (Washington: U.S. Government Printing Office)

- [9] Wilson I O 1981 Magnesium oxide as a high-temperature insulant *IEE Proc.* **128** 159–64
- [10] Webster E S 2017 Thermal preconditioning of MIMS type K thermocouples to reduce drift *Int. J. Thermophys.* **38** 5
- [11] McCulloch R W and Cliff J H 1982 Lifetime improvement of small-diameter sheathed thermocouples for use in high temperature and thermal transient operations *Temp. Meas. Control Sci. Ind.* **5** 1097–108
- [12] Scervini M and Rae C 2013 Low drift type N thermocouples for nuclear applications *3rd Int. Conf. on Advancements in Nuclear Instrumentation, Measurement Methods and Their Applications (ANIMMA) (Marseille)* (<https://doi.org/10.1109/ANIMMA.2013.6727899>)
- [13] Scervini M 2016 Development of low-drift nickel-based thermocouples for high-temperature applications *J. Eng. Gas Turbines Power* **138** 081601
- [14] Mella S, Löffler A and Schalles M 2021 Reliable multipoint temperature profiling in hydroprocessing units *Sensor and Measurement Science Int. Conf.* (<https://doi.org/10.5162/SMSI2021/C4.2>)
- [15] Loscoe C and Mette H 1962 Limitations in the use of thermocouples for temperature measurements in magnetic fields *Temp. Meas. Control Sci. Ind.* **3** 283
- [16] Beguš S, Bojkovski J, Drnovšek J and Geršak G 2014 Magnetic effects on thermocouples *Meas. Sci. Technol.* **25** 035006
- [17] Geršak G and Beguš S 2010 Thermometers in low magnetic fields *Int. J. Thermophys.* **31** 1622–32
- [18] BIPM 1997 *Techniques for Approximating the ITS-90* (Sèvres: BIPM)
- [19] Ford T D and Scervini M 2020 Low drift type K and N mineral insulated thermocouple cable for aerospace applications *TE Wire & Cable*
- [20] Machin G 2013 Twelve years of high temperature fixed point research: a review *AIP Conf. Proc. for ITS2012 (Los Angeles)* (<https://doi.org/10.1063/1.4821383>)
- [21] Jahan F and Ballico M 2003 A study of the temperature dependence of inhomogeneity in platinum-based thermocouples *AIP Conf. Proc.* **684** 469
- [22] Bentley R E 1998 *Theory and Practice of Thermoelectric Thermometry* (Singapore: Springer) p 63