

Temperature Calibration; Depths of Immersion

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Abstract

Of all the sources of errors and uncertainties in thermal calibration by far the largest source of error and least understood effect is that of immersion of unit under test, and the reference standard.

Little is written about this parameter as it is not considered part of the specification provided by a producer of calibration equipment, it is the responsibility of the user to evaluate the immersion properties of the sensors being calibrated.

In this paper immersion depths are considered in stirred liquid baths and in block baths, where there is an air gap.

Three levels of uncertainties are considered and how the accuracy required affects the immersion.

Graphs are presented that easily permit a user to gauge the depth of immersion required.

Practical examples are given.

1. Introduction

It is a fundamental of temperature measurement that temperature sensors measure their own temperature, and only when sufficiently immersed in the object whose temperature is desired will the sensor reach that temperature.

The purpose of this article is to develop some simple, practical rules to help when immersion depths are being considered.

2. Reviewing Existing Literature

The first place to look for guidance is a book called "Supplementary Information to the International Temperature Scale of 1990". It says:-

"A thermometer is sufficiently immersed when there is no change in indicated temperature with additional immersion in a constant temperature environment".

It then goes on to say:

"Although at temperatures above room temperature the required immersion depth initially increases with temperature, a maximum is reached at temperatures in the region of 400°C to

500°C, after which the rapidly rising radial heat transfer by radiation causes it to fall slightly; this is on the assumption of the presence of adequate longitudinal radiation baffles and the inhibition of radiation piping”.

Next place to look for practical information is the excellent book by Nicholas and White titled “Traceable Temperatures”. Fortunately they deal with immersion depths in a very practical way and are brave enough to put numbers to their descriptions. They say about immersion depth:

“The general problem occurs because there is a continuous flow of heat along the stem of a thermometer between the medium of interest and the outside world. Since heat can only flow where there is a temperature difference, the flow of heat is evidence that the tip of the thermometer is at a slightly different temperature than the medium of interest”. This is shown graphically in figure 1.0.

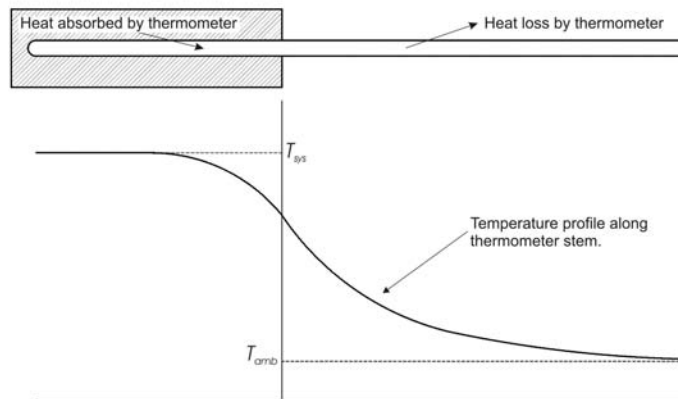


Figure 1.0. The flow of heat down the stem of a thermometer causes the thermometer to indicate temperatures slightly lower than that of the medium of interest.

A simple model of this effect relates the error in the thermometer reading to the length of immersion by:

$$\Delta T_m = (T_{amb} - T_{sys})k \exp\left(\frac{-L}{D_{eff}}\right)$$

Where T_{sys} and T_{amb} are the system and ambient temperatures respectively, L is the length of the immersion, D_{eff} is the effective diameter of the thermometer, and k is a constant approximately equal to, but less than 1. This equation, which is plotted in figure 1.1 for $k = 1$, is very useful for determining the minimum immersion which will ensure that the error is due to stem conduction is acceptable.

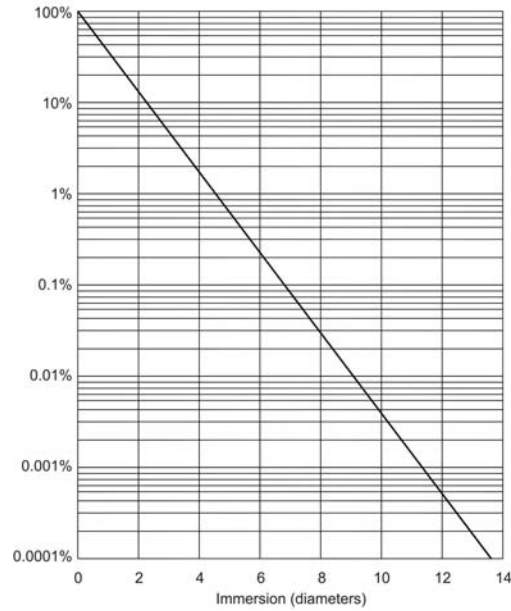


Figure 1.1. The relative temperature error $[\Delta T_m / (T_{sys} - T_{amb})]$ plotted against thermometer immersion length in diameters. This graph works well for sensors immersed in stirred liquid.

We recognise three useful rules of thumb from the figure:

- (i) for 'industrial' thermometry we recommend 5 diameter immersion suitable for 1% accuracy.
- (ii) for good laboratory thermometry we recommend 10 diameter immersion for 0.01% accuracy.
- (iii) for best laboratory practice we recommend 15 diameter immersion suitable for 0.0001% accuracy.

The length of the sensing element which would normally be a thermocouple junction, a themistor or a Pt100 element must be added to the immersion since none of the sensing element should be in the stem conduction gradient.

So there we have it; a formula that gives correct results in a "good stirred oil bath".

In the above formula we need to increase the immersion with temperature. However if we take the advice of ITS-90 Supplementary Information and calculate the depth at 500°C then this should be adequate for temperatures above 500°C.

Having identified 3 immersion depths for Industrial, Laboratory and Best practice the next section will deal with each of these in more detail.

3. Industrial Thermometry

Here we can site examples such as a thermowell and a dry block calibrator.

The thermowell is common and often has an outside diameter to length ratio of about 1:5 i.e. most industrial installations are designed for ~1% accuracy. They usually perform a little better than this because the thermowell does not protrude into the ambient space as a thermometer usually would (this gives a k value less than 1.0). The main point of the example is that we need to think about the outside diameter of the 'installation' and not in terms of the diameter of the probe within the thermowell.

The dry block calibrator is also a good example. Again one has to think about the diameter of the installation - in this case the diameter of the inserts (that have the thermometer wells drilled into them) mounted in the controlled space. The diameter is usually about 50mm, and if you're very lucky you might have an insert with a length of 250mm. Typically the temperature at the bottom of the insert is controlled to about 5% so there are large temperature gradients through the bottom of the insert. And no matter how thin your thermometer the immersion errors will normally be dominated by the poor immersion of the insert.

The insert immersion errors can be largely overcome if the standard to which industrial sensors are being compared is also placed in the insert and if the standard is of similar construction as the sensors being calibrated.

Sensors in thermowells or dry block calibrators will not absorb and lose heat in the same way in which they do in a stirred liquid bath and Nicholas and White's figure does not directly apply.

This is because they assume that they assume: $\frac{D_{(eff)}}{D} = 1$, which it is for stirred liquid baths.

However $\frac{D_{(eff)}}{D}$ will be greater than 1 if there is an air gap such as in a metal block calibration bath.

Let me therefore do a second example where we wish to calibrate a 6mm diameter thermocouple at 500°C above ambient in a metal block bath to an accuracy of 0.5°C.

$$\left| \frac{\Delta T_m}{T_{sys} - T_{amb}} \right| = \frac{0.5}{500} \approx 0.1\%$$

Then referring to figure 1.1 I found that for $D_{(eff)} = D = 1$ the minimum immersion is 7 diameters or 42.00mm. However, if $D_{(eff)} = 2D$ then this would increase to 84.00mm.

What Nicholas & White do not do is to give figures of $\frac{D_{(eff)}}{D}$ for metal block calibrators.

Fortunately at the Northern Temperature Primary Laboratory we have evaluated fully many metal block baths of our own design at various temperatures over a number of years. Using the figure of 0.5°C as a criterion I find in general, almost irrespective of the temperature (tests were conducted at 250°C , 450°C and 650°C) that 80mm immersion was required for a 6mm type N thermocouple in a 6.50mm hole for stem conduction / vertical thermal profile of the metal block insert to be less than 0.5°C , thus confirming a figure of $\frac{D_{(eff)}}{D} = 2$.

For industrial platinum thermometers we must add around 40mm for the sensor making 120mm. However we need greater accuracy than with thermocouples (say 0.05°C) thus we need to immerse a further 25mm, making a total of 145mm of immersion.

Thanks to the combined efforts of the above authors it is possible to generate some rules that are truly practical. We can use figure 1.1 for stirred liquid baths and figure 1.2 for metal block baths with small air gaps.

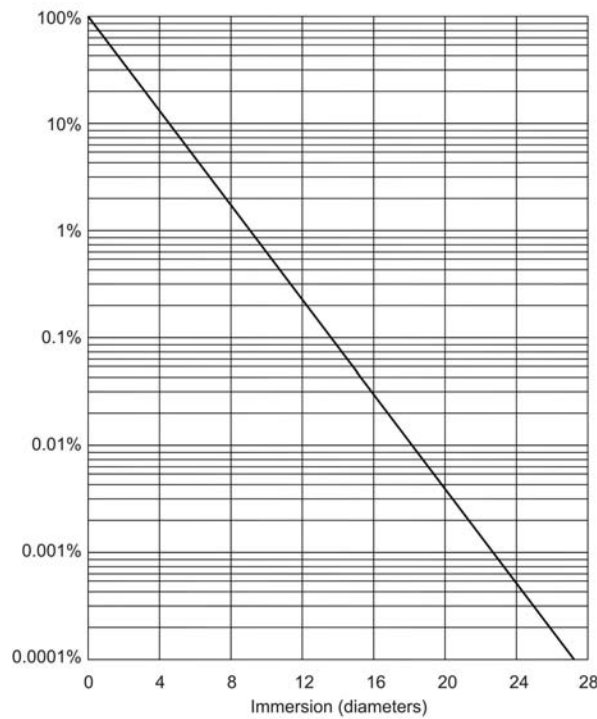


Figure 1.2. The relative temperature error $[\Delta T_m / (T_{sys} - T_{amb})]$ plotted against thermometer immersion length in diameters, where $\frac{D_{(eff)}}{D} = 2$, such as a dry block calibrator.

Most good quality portable metal block baths have immersions of around 150mm. However as can be seen from the above as the diameter of the sensor to be calibrated increases we need greater immersions or we must reduce the accuracy of the calibration.

4. Laboratory Thermometry

Here we can take the example of a stirred liquid bath and use the figure 1.1

Example

Determine the minimum immersion for a 4mm diameter sheathed thermometer with the detecting element occupying the last 40mm of the sheath. The measurement should have immersion errors of less than 0.01°C for temperatures up to 100°C.

First we determine the relative accuracy in the measurement as:

$$\left| \frac{\Delta T_m}{T_{\text{sys}} - T_{\text{amb}}} \right| = \frac{0.01}{100 - 20} \approx 0.01\%$$

Then, referring to figure 1.1, we find that the minimum immersion is a little more than 9 diameters. To be conservative we will immerse the thermometer to 10 diameters beyond the detector element, i.e. 80mm total immersion. Ten diameters is a useful rule-of-thumb for accurate thermometry ($\sim\pm 0.01\%$). Five diameters are more typical of industrial thermometry ($\sim\pm 1\%$).

5. Best Laboratory Practice

The most exacting measurements made are the Standard Platinum Resistance Thermometers in Fixed Point Cells.

The immersion of the thermometer in the metal of the fixed point cell is only 160mm to 200mm and an SPRT may require 300mm immersion. So how is it that the most exacting measurements in the World are made in the cells with blatantly lack of immersion depth?

The answer is simply that the temperature, above the cell and for a further 200mm is within, typically, 0.5°C of the cell itself thus the temperature gradient is only 0.5°C. This reduces the immersion depth required.

For example take a Zinc cell, with 200mm immersion.

$$T_{\text{amb}} - T_2 = 400^\circ\text{C}$$

If ΔT_m required is 0.0001°C

Then we look at $\frac{0.0001}{400}$ or about 32 diameters + sensing length. (From figure 1.2 since the thermometer is in an air gap)

Now consider $T_{\text{amb}} - T_2 = 0.5^\circ\text{C}$

Now the measurement becomes $\frac{0.0001}{0.5} = 0.0002$ or only 16 diameters + sensing length.

A saving of 128mm of immersion for an 8mm diameter SPRT.

So in this example the depth of immersion required for accurate measurement is decreased because the temperature difference between the thermometer in the cell and in the apparatus just above it is small, typically 0.5°C.

6. Discussion

The above review shows ways of predicting the immersion depth required for various temperature sensors at various temperatures and of varying diameters.

The practical figures should enable the reader to better design an industrial installation or select calibration equipment.

One word of caution however the above is a guide only. There are always exceptions, so follow Nicholas & White's advice:

"In all cases where immersion errors are suspected it is a very simple matter to vary the immersion depth by one or two diameters to see if the reading changes. As a crude approximation about 60% of the total error is eliminated each time the immersion is increased by 1 effective diameter".

References

1. Traceable Temperatures., J.V. Nichols & D.R. White. ISBN 471-49291-4
2. Supplementary Information for ITS-90. ISBN 92-822-211-3

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