MSL Technical Guide 11

Thermometer Immersion and Dry-Block Calibrators

Introduction

Dry-block calibrators are widely used throughout industry to aid calibration and maintenance of temperature measurement and control systems. Their main advantages are convenience and safety – they are portable, compact, and contain no hot or flammable working fluids. Unfortunately, they have limitations that may not be obvious to the user.

The purpose of this technical guide is to provide users with a simple method for assessing the quality of thermometer immersion in dry-block calibrators.

Although the test method describes the testing of dry-block calibrators, it can also be used to assess the quality of immersion in any furnace, calibration bath, oven, etc.

Thermometer Immersion

All contact thermometers suffer from immersion errors. This happens because heat is lost up the sheath or lead wires of the thermometer, leading to a small temperature gradient in the vicinity of the sensor. Figure 1 shows how the temperature varies along the length of the thermometer. Having an insufficient length of thermometer immersed can cause errors as large as several tens of degrees in some industrial installations.

As Figure 1 shows, immersion errors are made smaller by immersing the thermometer further into the object of interest, which may be a dry-block calibrator, a furnace, or a laboratory water bath, for example.

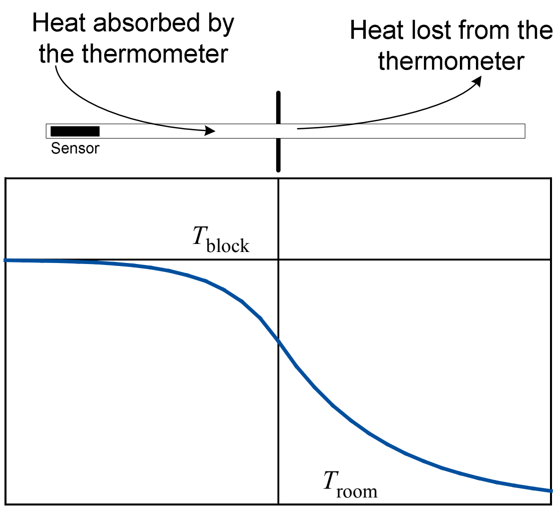

Figure 1. The typical temperature profile along the length of a thermometer.

As a rule of thumb, thermometers immersed to five times their diameter are accurate to about 1 %, and this is sufficient for most industrial installations. For example, if the temperature of interest is 120 °C and the room temperature is 20 °C, then the difference is 100 °C. A 1 % error leads to a temperature error of about 1 °C. Installations in testing and calibration laboratories often require an accuracy of between 0.1 % and 0.01 %, which may require immersion to more than ten times the diameter of the thermometer.

Dry-Block Calibrators

Dry-block calibrators are typically an aluminium or copper block surrounded by a heater (see Figure 2). In some cases, they may also have Peltier cooling so that they can operate below room temperature. The block will usually have between two and six wells for inserting thermometers for calibration.

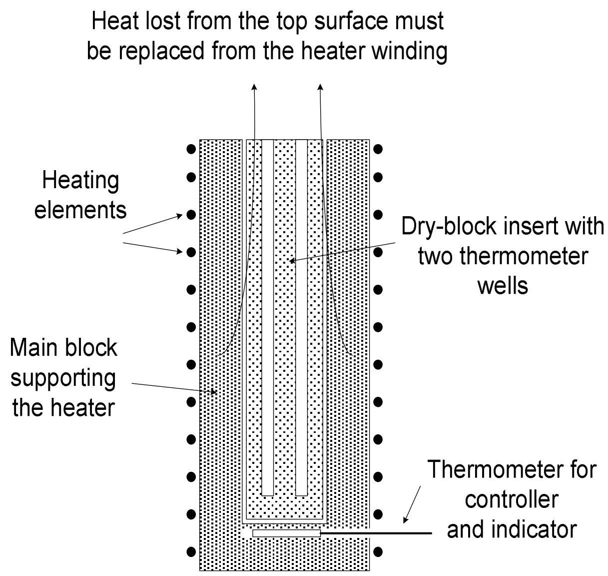

Figure 2. A typical dry-block calibrator. The heat flow from the heater to the top surface leads to a large temperature gradient in the block

There are two causes of immersion problems with dry-block calibrators. The first has to do with the immersion of the thermometer, as already explained. The second has to do with the immersion of the block itself. As Figure 2 shows, the block is immersed in a heated zone, perhaps about 150 mm deep and about 30 mm in diameter. That is, the dry-block immersion is probably only about five times its diameter: The temperature gradients in the block possibly cause errors as large as 1 % near the bottom of the thermometer wells.

In practice, the problems are not quite this bad. Usually, the block does not extend out of the heated zone, so the only heat loss is to the air through the top surface of the block. Secondly, the manufacturer will have positioned the indicating thermometer so that it reads very close to the temperature at the bottom of the wells.

Testing the Dry-Block

We can assess the quality of the immersion of a thermometer simply by plotting a graph of temperature reading against the immersion depth. In this section we describe the mathematical model used to develop the method. If you're not interested in the model, skip this section and move on the to example.

The accuracy of thermometers varies with immersion according to a fairly simple mathematical equation:

$$T_{\text{reading}} - T_{\text{block}} = \left(T_{\text{room}} - T_{\text{block}}\right) K \exp\left(\frac{-L}{D}\right),$$

where:

- T_{reading} is the thermometer reading;
- T_{block} is the true block temperature;
- T_{room} is the background temperature of the room;
- L is the length of thermometer immersed into the block;
- D is a constant related to the diameter of the thermometer; and
- K is a constant that depends on the size and thermal conductivity of the block and thermometer.

The equation shows that the error decreases exponentially as the immersion length increases.

The equation can be rearranged into a form better suited to our analysis:

$$\ln\left(\frac{T_{\text{reading}} - T_{\text{block}}}{T_{\text{room}} - T_{\text{block}}}\right) = K - \frac{L}{D}.$$

Therefore, by plotting on a graph the log of the temperature error (left hand side) against the immersion length, L, we should get a straight line.

An Example

First, set the dry-block calibrator (or furnace, calibration bath, etc) at a convenient temperature and wait for the reading to stabilise. A temperature above room temperature, say 50 °C to 100 °C, is a good choice to begin with. Initially, have the thermometer fully immersed in the block. You may need a clamp stand or similar device to hold the thermometer in place when it is not fully immersed.

Step 1: Once the thermometer reading and the dry-block indicator reading have stabilised, withdraw the thermometer so it is only just immersed in the dry block.

Step 2: Once the thermometer and the dry-block indicator have stabilised, record the thermometer reading and the immersion length.

Step 3: Lower the thermometer a further 1 cm into the dry-block. Repeat Step 2 and Step 3 until the thermometer is fully inserted into the block.

You should now have a table of data very much like Table 1.

Table 1. Immersion data for a dry-block at 50 °C.

Immersion / cm	Thermometer reading / °C
0	44.8
1	47.7
2	49.2
3	49.7
4	49.9
5	50.0

To analyse the results it will be very helpful if you have access to a computer with a spreadsheet application, but it is not essential. Now expand the table to do the following calculations

Step 4: Set aside a separate cell in the spreadsheet for the block temperature. Set the initial value to 50.1 – a little higher than the temperature reading at full immersion.

Step 5: Set aside a second cell for the room temperature. Set the initial value to what you think is close to the room temperature – this number is not critical. In the example it is set to 20 °C.

Step 6: Calculate entries for a third column in the table for the temperature error. This is calculated as the thermometer reading minus the block temperature.

Step 7: Calculate entries for a fourth column in the table for the percentage error. This is calculated as the entry in the third column multiplied by 100 and divided by (room temperature minus block temperature). Table 2 shows what your spreadsheet should look like so far.

Table 2. The intermediate calculations for the immersion spreadsheet.

Block temperature			50.1
Room temperature			20
immersion cm	reading	estimated error	relative error (%)
0	44.8	-5.3	17.61
1	47.7	-2.4	7.97
2	49.2	-0.9	2.99
3	49.7	-0.4	1.33
4	49.9	-0.2	0.66
5	50	-0.1	0.33

Step 8: Use the chart feature of the spreadsheet application to create a graph of the percentage error versus the immersion. Double-click on the vertical axis of the graph and set the scale to logarithmic scale. You should now have a graph that looks similar to Figure 3.

Step 9: Now adjust the value for the block temperature to make the line appear straight. In the example a block temperature near 50.06 °C seems like a good choice.

Step 10: Now read off the error for full immersion from the table. With the adjusted value for the block temperature, it will be about –0.06 °C or 0.2%. These numbers are an estimate of the immersion error for the thermometer.

Step 11: Save the spreadsheet under a different file name so you can use it as a template for other immersion tests.

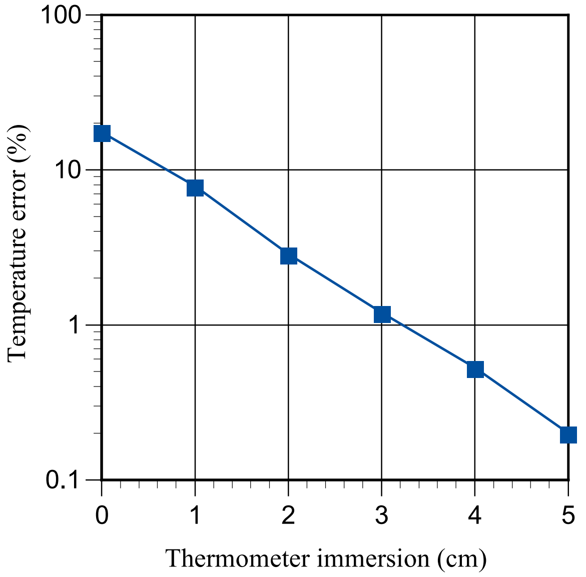

Figure 3. Plot of the thermometer error versus immersion. This should be a straight line on this semi-log graph (the vertical axis is logarithmic and the horizontal axis is linear).

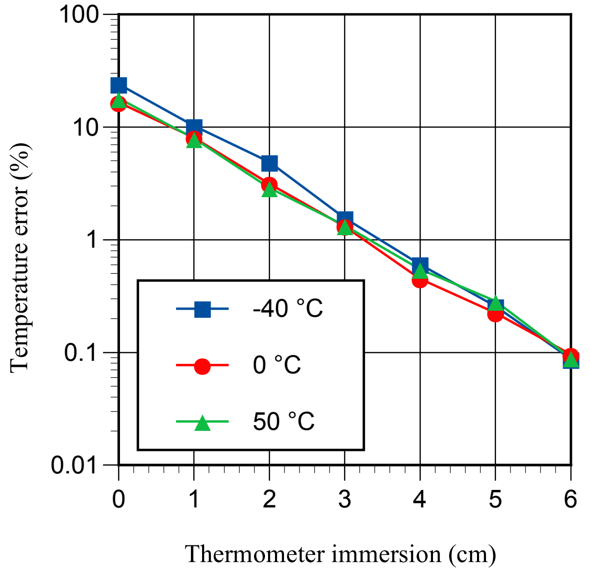

Figure 4. The temperature error graph should be similar at different temperatures. These results are for a dry-block calibrator.

Further tests

If you are seeking accreditation for a calibration or testing laboratory, you should test your dry-block calibrator (or calibration bath) at three different temperatures – one near the highest temperature you will use, one at the lowest temperature, and one near the middle of the range. In a dry-block, the immersion characteristics for the thermometer will be very similar at all three temperatures. In an oil bath, you may find the profile is better at high temperatures where the oil is less viscous. Figure 4 shows the immersion profiles for a dry-block calibrator tested at –40 °C, 0 °C, and 50 °C.

Ideally, when calibrating other thermometers, you should use an independent and calibrated reference thermometer in a thermometer well next to the thermometer under test. If you are using the dry-block to calibrate different types of thermometers it pays to do an immersion test for each type, including the reference thermometer. Figure 5 shows the immersion profiles for two industrial platinum resistance thermometers (IPRT). Both of the thermometers are immersed into an oil bath at 60 °C. One has a 10 mm diameter steel sheath, the other a 4 mm diameter sheath. This shows that the larger the diameter, the worse the immersion error.

The smaller IPRT of Figure 5 shows another interesting effect. The strange behaviour in the first 30 mm of immersion for the 4 mm thermometer indicates the location of the sensing element.

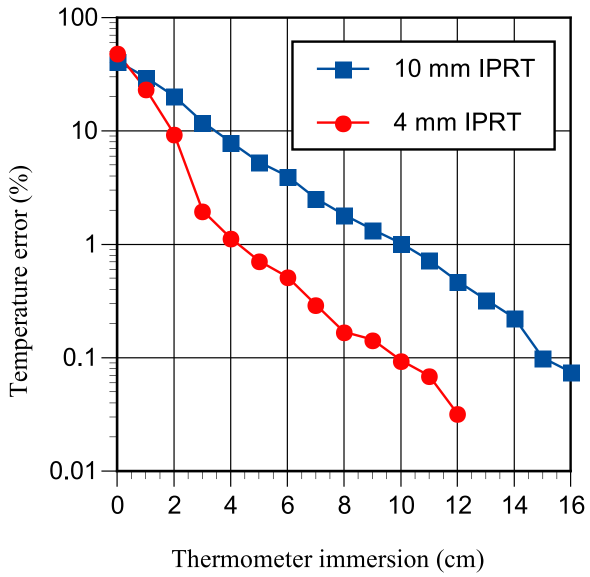

Figure 5. The immersion profile for two industrial platinum resistance thermometers in a calibration bath.

Prepared by D R White, June 2006.