# Precise calibration requires identical temperature sensors

Ideal calibration requires that the zeroth law of thermodynamics be met. Every deviation from that law increases the uncertainty of the correction value you are trying to determine. This article discusses some factors that increase uncertainty and suggests how you can improve your calibration in practice.

The theory states that to achieve perfect calibration, the zeroth law of thermodynamics must be met. See Figure 1. This law states that if two systems (S1 and S2 with the temperatures T1 and T2) are each in thermal equilibrium with a third system (S3 with the temperature T3) then both the first two systems (S1 and S2) are in thermal equilibrium with each other. There is no heat exchange with the surroundings. The term 'thermal equilibrium' means that the same amount of thermal energy is flowing to each body as is flowing from each body, that is, the net flow to the body is zero. The significance of this is that all the systems have the same temperature. (T1 = T2 = T3).

Figure 1. The zeroth law of thermodynamics. For thermal equilibrium to occur between all three bodies, S1, S2 and S3, they must have the same temperature: T1 = T2 = T3. Unfortunately, this is an ideal situation that is impossible to achieve, because heat exchange with the surroundings cannot be avoided. See further Figure 2.
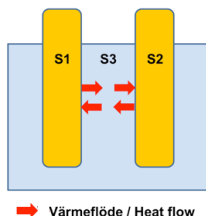
If we suppose that S1 and S2 are temperature sensors and S3 is a block oven or water bath, this ideal situation is complicated by additional thermal flows, which appear disruptive. The thermal flows are driven by the temperature difference between the insulated volume and the surroundings. See Figure 2. In the real world, perfect insulation does not exist and a temperature sensor must be connected to the outside world via a connection cable and protective tube. The result is that the heat that is conducted out from the calibration volume (S3) must be removed from that volume. The same applies to sensors S1 and S2. In turn, this means that sensors S1 and S2 lose their thermal equilibrium with the calibration volume S3.

Inside calibration equipment, a constant temperature is maintained by a control system that adapts the heating or cooling to the prevailing heat losses or gains respectively. However, this does not prevent the thermal flows from reaching the outside environment via the insulation, sensor protection tubes and cabling.
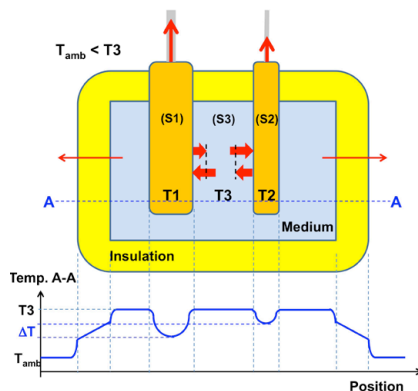
Figure 2. A hypothetical but realistic depiction of real-life calibration. Heat exchange with the surroundings means that perfect thermal equilibrium is impossible to achieve. Differences in the sensors' physical construction such as the cross-section area cause differing thermal flows to the surroundings and thereby different temperatures in the respective sensor components.

Equal loss is best

As long as the temperature sensors – the reference and measurement objects – are constructed identically in terms of their materials and dimensions, and are also placed in the same way in the calibration bath or metal block, their deviations of thermal equilibrium will be similar and therefore the temperature difference (ΔT) between the probe tips will be minimal even though it will be at a slightly deviating temperature level. The greater number of physical differences that exist between the sensors, the greater is ΔT. See the temperature distribution in Figure 2.

Similarly, differing insertion depths can cause different temperatures at the probe tips. See Figure 3.

Due to the heat flow out from the calibration oven, the temperature decreases axially the closer we come to where the sensor enters the oven. This phenomenon is not very pronounced in liquid baths that are stirred but is more of a problem in block ovens.

Correct for measurement error

In the case of known deviations you can correct for the calibration's measurement error and thereby reduce the remaining measurement uncertainty. Known deviations mean that "someone" – that is, the manufacturer or you yourself – has measured the block calibrator's temperature distribution axially and radially inside the block under specified thermal loads. See further [Ref 1]. In general, calibration using block calibrators produces measurement uncertainties that are at best about a few tenths

of a degree at low temperature. Hybrids with water or oil in the bottom of the hole improve the situation. At higher temperatures, up around 600 °C, the uncertainty can very well increase to the level of whole degrees. Read more about block calibrators in [Ref 2].

Calibration in a liquid bath using water, an alcohol-water mix, or oil gives significantly better accuracy, especially for water in the range of 0 < T < 100 °C. Under favourable conditions in a laboratory setting it is possible to get down to the mK level. It is more common to achieve hundredths of a degree, whilst ordinary heat-retention baths with circulation can often achieve tenths of a degree. The latter may need to be equipped with a lid and/or plastic spheres on the surface of the water in order to reduce evaporation and heat losses. Read more about liquid baths in [Ref 3].

Unfortunately, ideal calibrations do not exist. However, it is possible to reduce the sources of error by using reference sensors that are physically as identical as possible to the measurement objects. This applies primarily to the thermal flow along the axial direction, which is affected by such factors as the dimension of the protection tube, and to the heat transfer radially into the sensor component in the probe tip. ▯
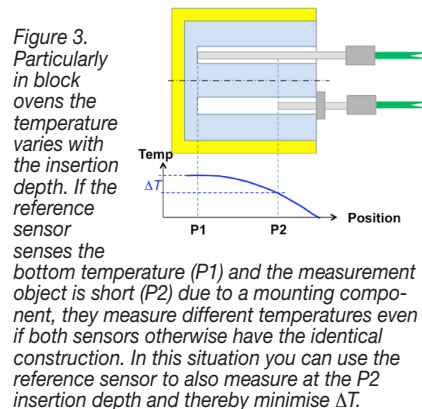
Figure 3. Particularly in block ovens the temperature varies with the insertion depth. If the reference sensor senses the bottom temperature (P1) and the measurement object is short (P2) due to a mounting component, they measure different temperatures even if both sensors otherwise have the identical construction. In this situation you can use the reference sensor to also measure at the P2 insertion depth and thereby minimise ΔT.

References see www.pentronic.se > News > Pentronic News > Pentronic News Archive
[Ref 1] Pentronic News 2009-1
[Ref 2] Pentronic News 2009-2
[Ref 3] Pentronic News 2009-3

If you have questions or comments, contact Hans Wenegård: hans.wenegard@pentronic.se