INDUSTRIAL MEASUREMENTS WITH VERY SHORT IMMERSION

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Abstract

One major problem that keeps recurring is the request to calibrate, or in some other way to evaluate, very short industrial temperature sensor assemblies. These sensors are so short that the sensor does not attain the temperature of its surroundings.

Two distinct methods are possible, in method one the assembly is immersed in a comparison bath sufficiently to eliminate the stem conduction effect, even if this method creates a different result than achieved in-situ.

Method two attempts to simulate the application in practice and provide a similar stem conduction error as the assembly sees in practice.

Introduction

As a rule of thumb for a temperature sensor in a stirred liquid to measure within 1%, it needs to be immersed five times its diameter plus the probes sensing length.

If a thermowell is used or another air gap introduced the immersion needs to increase to 10 times the diameter plus the sensing length.

Yet in many measurement situations, e.g. measuring engine bearing temperatures immersion is very short and in the extreme situation of surface temperature measurement there is no immersion at all.

The basis of accurate calibration (and of course accurate temperature measurement) is found in the Zeroth Law of Thermodynamics, the implication of which is that a sensor must be sufficiently immersed, such that further immersion makes no difference to the temperature reading of the thermometer.

Short sensors and surface sensors by definition do not comply with the Zeroth Law, but we still require knowledge of their performance. This presentation investigates the problems and suggests solutions for discussion.

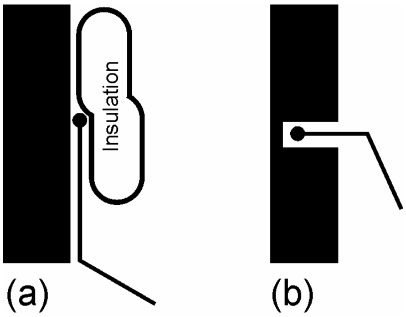
Surface temperatures

Surface-temperature measurements are fundamentally difficult. The problem is that a surface is an infinitely thin boundary between two objects, and therefore there is no ‘system’ into which to immerse a thermometer. ‘What is the surface temperature?’ is therefore a silly question. With surface-temperature measurements the answer to the measurement problem often lies in analysing the purpose for making the temperature measurement. For example, if we need to know how much energy the surface radiates, we should use a radiation thermometer; if we want to know the likelihood of the surface posing a human burn risk then we should use a standard finger as specified by a safety standard; and if we require a non-intrusive measurement of the temperature of the object behind the surface, then a measurement using one of the techniques in Figure 1 may be the answer.

In recent years, there has been a huge increase in the number of commercially available surface probes, which are often thermocouple based. Unfortunately, the inherent design of most of them is seriously flawed. They often use quite heavy thermocouple wire, the measurement junction is not isothermal in use and they approach the surface at right angles where the greatest temperature gradients occur. As a result, most commercial surface probes are in error by about 5% to 10%. With careful design, fine wire placed along the surface, and insulation behind the wire, accuracy’s of about 1% are readily achievable.

Surface-temperature measurements are also subject to errors caused by the probe inhibiting the emission of radiation from the surface.

Figure 1. Methods of Accurately Measuring Surface Temperature.



Two solutions to the problem of surface-temperature measurement:

(a) attaching a length of the probe to the surface. Here the probe is immersed along an isotherm improving immersion – in some cases insulation may be helpful in reducing heat loses by radiation or convection, although it can cause the surface increase in temperature.

(b) Here the surface is approached from the side that has the least temperature gradient and gives the least error.

Surface Sensor Calibration (Or Simulation?)

The two main problems are understanding the conduction properties of the surface sensor and knowledge of the calibration surface. With many surface sensors only the sensor tip touches the surface with the sensor body at or close to ambient. Under these conditions all that can be said is that the reading will be somewhere between the surface temperature and ambient. The offset from the surface temperature will vary depending on the surface roughness, its emissivity, its elevation from ambient temperature, whether conducting greases are being used, and whether the air surrounding the sensor is still or moving.

Causes of Measurement Error

Foulis, [1] Michalski et al [2] identifies three main problem areas in determining the surface temperature of a solid which is in equilibrium with the surrounding atmosphere. We can call these the first, second and third partial errors.

The first partial error results from the loading effect on the object being measured by bringing a cold measuring probe into contact with it. The heat flow from the surface of the object in contact with the probe increases from its equilibrium value as flux is drawn up the probe. The result is a disturbance of the temperature field and a drop in surface temperature at that point. The error is particularly severe with non-metallic objects, where the low thermal conductivity of the object results in large temperature field disturbances.

The second partial error is due to the non-ideal thermal contact condition between the probe and the surface of the object, resulting in a thermal resistance at the interface between the two. The situation is analogous to electric current flowing through a resistance, causing a voltage drop across the resistor.

The third error is caused by the temperature drop with distance from the surface of the object being measured to the 'sensitive point' of the probe at which the temperature readings are taken. In most contact probes thermocouples are used as sensors, and due to the practical constraints of thermocouple construction the junction is offset by some distance from the physical tip of the sensor.

These three errors can be represented by the following equations [2]:

$$e_1 = -(R_T / l_b)(F_m) \bullet q_d \qquad \text{Eq. 1}$$
$$e_2 = -W_C \bullet \varnothing_T \qquad \text{Eq. 2}$$
$$e_3 = -l / l_T \bullet q_T \qquad \text{Eq. 3}$$

where q_d = net heat flux density up the probe.
q_T = total heat flux density up the probe.
$\varnothing_T$ = total heat flux up the probe.
R_T = radius of the probe.
l_b & l_T = thermal conductivities of the object and probe.
W_c = contact resistance.
F_m = a constant.

From the equations, it may be seen that all three system errors are proportional to either the heat flux or the heat flux density that flows up the measuring probe due to the temperature gradient between the object and the probe. If this heat flux can be reduced, then it follows that the measurement errors will also be reduced.

A Thermally Compensated Probe

The intense heat flux which flows up the probe when it is brought into contact with the object being measured is the result of a large temperature difference between the hot object and the cold probe. If that temperature gradient can be reduced before the probe is brought into contact with the object, the heat flux, and consequently the three partial errors, will be reduced.

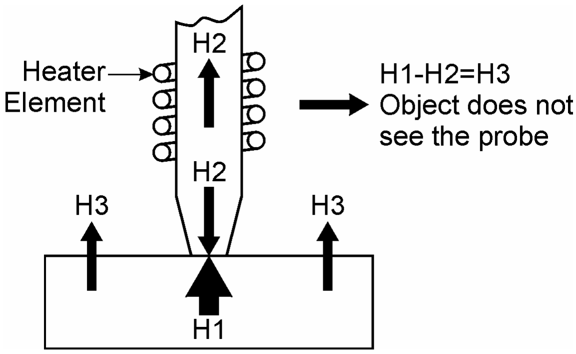


Figure 2. A Schematic of a Thermally Compensated Sensor.

A schematic of a thermally-compensated probe is shown in Figure 2. It is based on a principle proposed by Stamper and Emelyanenko [3], [4]. A heater element is wound around the probe near the sensing tip, and is used to raise the temperature of the probe to the same temperature is that one of the object being measured. When the probe is brought into contact with the object, the temperature field at the object surface is no longer distubed, because the difference between the heat flux H1 drawn up be the probe, and the heat H2 supplied by the object, is approximately equal to the equilibrium heat flux H3 that would flow into the atmosphere if the probe were not present.

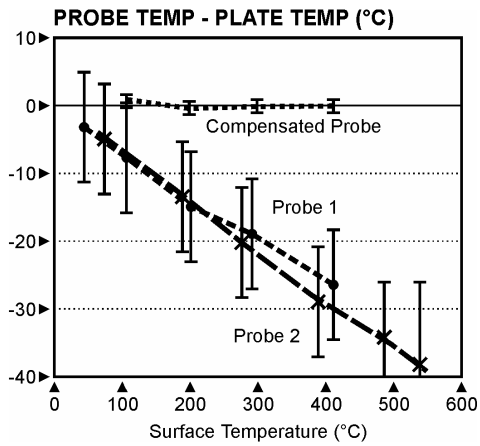


Figure 3. A Comparison Between The Thermally Compensated Probe & Two Standard Probes.

A comparison between the thermally compensated probe and two standard probes is shown in Figure 3. The reduction of heat flux up the probe resulted in a large reduction in the measurement errors. Furthermore, the temperature field of the object is not disturbed, and thus a measure of the true unloaded surface temperature can be made. Automaticlly Compensated Probes, such as Isotech's Model TTI 4 are Thermocouple (T/C) based devices where the temperature of the surface is sensed by T/C junction 1, and T/C junction 2 senses the temperature gradient along the T/C,as shown in Figure 4 This gradient or temperature difference signal is fed into the temperature controller which applies heat to the probe stem so as to reduce the gradient to zero. When there is no heat transfer from the surface to the probe junction 1 is now measuring the undistirbed surface temperature, UST, which is displayed on the indicator.

Calibration And Traceability

There are no internationally recognised standards for surface temperature. The Dutch National Laboratory (NMi) under Martin De Groot have devloped a traceable calibration method that involves predicting the surface temperature from measurements made with resistance thermometers located along the length of a copper bar immersed in an oil bath. Isotech have also devloped a different traceable calibration method that uses T/C's set into the surface of an aluminium bar such that the surface acts as the junction between the T/C wires. An informal audit using an Isotech TTI 4 surface temperature thermometer standard over the range 50°C to 300°C gave results that agrees within $\pm\sqrt{(0.5^2 + 2^2)}$, where ±0.5°C us the uncertainty of calibration of NMi and ±2°C is the uncertainty of calibration at Isotech.

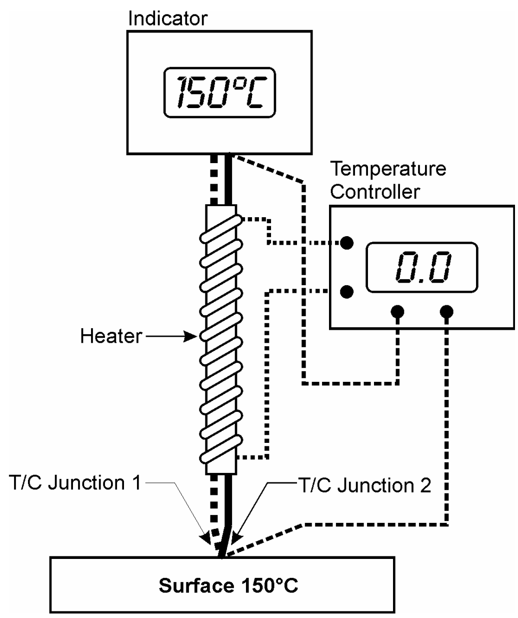


Figure 4. Automatic Thermally Compensated Probe With Control & Indication.

In Great Britain the majority of UKAS laboratories calibrate passive surface temperature probes by immersing them into isothermal volumes as they would immersion thermometers. This enables them to issue a ‘valid’ certificate but this type of calibration does not reflect the errors and uncertainties of the probe when it is used as a surface thermometer. An example of the problems this type of calibration can cause was when Isotech was asked to act as a third party in a dispute between a drugs company and a UKAS laboratory. Using the immersion method, the UKAS laboratory had calibrated the drug company’s hand held digital indicator,DTI, fitted with a passive T/C probe and given a table of results which showed it was within ±2°C of the measured temperature to an uncertainty of ±1°C. When the drugs company used it to measure surface temperature they realised that something was wrong. They then sent it to us for a calibration using our surface standards. When we calibrated the DTI and probe we found it to be reading 20°C low at 250°C and due to its lack of repreatability, we gave it an uncertainty of ±5°C.

There is a potential here for a disaster in that if this particular DTI and probe were used to set the temperature of a hot plate that was used to seal plastic tops to blister packs containing drugs, it could well have been set incorrectly. This could have meant the drugs were not in sterile packaging because the top was not sealed to the container or that the drugs could have been damaged by excessive heat.

The Future

Surface temperature is growing in importance in a wide range of industries but there is little interest in developing surface temperature standards. NMi have traceable standards that cover the range 50°C to 300°C, and Isotech have traceable standards that cover the range –45°C to 650°C. We are both working to improve our capabilities and Isotech have approached UKAS about becoming accredited for surface temperature. UKAS have suggested a possible way forward for us to achieve this which we will progress this year.

Short Sensors

Temperature sensors measure their own temperature only. An obvious statement but it leads to 95% of all bad measurements when forgotton.

Nichols & White [5] have shown in their excellent book ‘Traceable Temperatures’ that for a temperature sensor in a flowing liquid to be within 1% of the actual temperature it needs to be immersed five times its diameter plus its sensing length. If an air gap is introuduced it changes to ten times the diameter plus sensing length.

In the extreme, a sensor needs immersion 15 times its diameter in a moving liquid to be within 0.001% of the liquid’s temperature when directly immersed in the liqiud.

Industrial sensors are frequently immersed much less than this and often in unfavourabel conditions yet users have the expectation that they can be relied upon for accurate temperature measurement.

So how should such short sensors be calibrated?

Three main solutions are used:-

1. In this method the short sensor with its leads is placed into a pocket long enough that it can be immersed sufficently to meet the Zeroth Law of Thermodynamics.

   This method is useful in tracking any sensor drift due to contamination or vibration that may have occurred but it does not help tell the actual temperature of the process.

2. Simulation rather than calibration.

   It involves knowing the application and agreeing with the user what they require. This often involves building a special block for a calibrator and also a special sensor that has the same thermal characteristics as the sensor being calibrated but is often longer so that it can be calibrated with sufficient depth. Once calibrated the special sensor is then placed alongside the short sensor to a similar depth and assuming similar stem conductions the sensors may be compared.

3. A third, but seldom used method is to try and calibrate the sensor in-situ only applicable in some situations a calibrated sensor of sufficient immersion is used to measure the process temperature close to the sensor being calibrated, and the temperatures compared.

Design Changes That Can Reduce Errors

In the three diagrams, shown in Figure 5, particularly for flowing fluids and gases the short sensor design is replaced with longer sensors by firstly understanding the problem and secondly changing the access to the fluid being measured to permit longer immersion in the fluid.

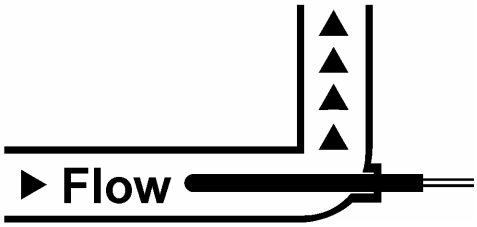


Figure 5a

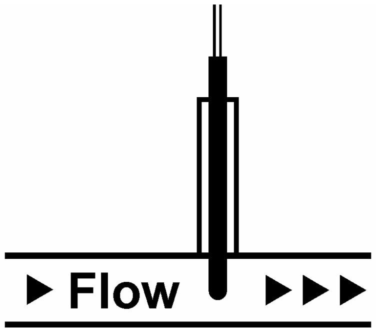


Figure 5b

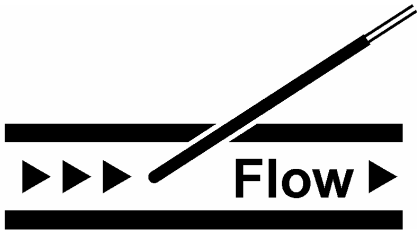


Figure 5c

Conclusion

Good results can be obtained from short or surface sensors provided the user and the laboratory calibrating (or simulating) the sensor can meaningfully decide how the sensors performance is to defined.

This can involve extra costs in building thermal simulators and specially designed standards that thermally match the sensors whose charateristics are required.

More thought at the design stage of a measurement problem involving solutions with longer immersion would save costs later on when calibration is contemplated.

Normal calibration requiring long immersion depths is not practical and carefully thought out simulations are required if meaningful results are to be achieved.

References

[1] Bruce D. Foulis, “Surface Temperature Measurement Using Contact Thermometry”, Isotech Journal of Thermometry, Vol 6, No 2 1995.

[2] L. Michalski, K. Eckersdorf, J. McGhee, Temperature Measurement, John Wiley & Sons, New York and London, 1991 pp 317-350.

[3] J. A. Stamper, “Differential Sensing Controlled Thermocouple”, Review of Scientific Instruments 34, 1963, pp 444-445.

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[5] J.V. Nichols & D. R. White, Traceable Temperatures, Wiley & Sons Ltd.