MSL Technical Guide 22

Calibration of Low-Temperature Infrared Thermometers

Introduction

The advent of low-cost handheld infrared (IR) thermometers has led to a proliferation of non-contact temperature measurement in the food, building, and low-temperature processing industries. However, these instruments are not as simple to use as they first appear due to systematic effects that are present in almost all measurements.

This technical guide provides information relating to the calibration of "low-temperature" IR thermometers, which typically measure temperatures in the range –50 °C to 500 °C (see Figure 1). These thermometers commonly use uncooled thermopile detectors that detect radiation in the 8 μm to 14 μm spectral range (or similar). Because these detectors are uncooled, radiation emitted by the detector itself must be considered in the calibration process. The emissivity setting on the thermometer, which is often fixed at a value of 0.95, and any radiation reflected from the surroundings, must also be taken into account.

As a consequence of these systematic effects, calibration methods are more complicated than for contact thermometers or high-temperature IR thermometers. The expected reading, even on a perfect IR thermometer, does not necessarily match the reading of the reference thermometer. Procedures for determining the required corrections are given in this guide.

Figure 1. A typical low-temperature handheld infrared thermometer. Photo courtesy of Fluke Corporation, reproduced with permission.

The guide begins by briefly outlining the principles of infrared thermometry and giving details of the measurement processes employed inside the thermometers themselves. By necessity, there is some mathematical detail that can't be avoided for any laboratory wanting to set up IR thermometer calibration procedures. However, once understood, the mathematics can be easily implemented in a spreadsheet application. A sample Excel spreadsheet is available for download with this guide.

How IR Thermometers Measure Temperature

Electromagnetic Spectrum

All objects emit radiation in the form of electromagnetic waves. This radiation is distributed across the electromagnetic spectrum, from radio waves, through microwaves, infrared radiation, visible light, ultraviolet light, and x-rays, to gamma rays. The actual distribution and intensity of the radiation emitted by a specific object is largely determined by the temperature of the object. For objects near room temperature, almost all of the emitted radiation is contained within the infrared part of the spectrum, at wavelengths in the vicinity of 10 microns (10 μm). For objects near 1000 °C, the radiation is centred near the shorter wavelength of 2 μm.

By measuring radiation at a fixed wavelength, or more correctly over a fixed wavelength range, an IR thermometer can determine the temperature of an object from the intensity of the signal measured at the output of its radiation detector – the higher the signal the higher the temperature. Many IR thermometers are designed to measure radiation over the wavelength range 8–14 μm, and these instruments are suitable for measuring temperatures in the range –50 °C to 500 °C, and sometimes higher. For temperatures outside this range, thermometers operating at different wavelengths are better suited.

Thermometer Response Function

The measured signal is usually a current or voltage at the output of the IR thermometer's detector. This is not usually of much use to the user, who wants to know the temperature that this signal corresponds to. It turns out that the signal varies in a highly non-linear fashion as a function of the temperature of the target object. This non-linearity means, for example, that twice the signal does not correspond to twice the temperature. The relationship between detector signal and temperature is given by a thermometer response function, which is well-approximated by the equation:

$$S(T) = \frac{C}{\exp\left(\dfrac{c_2}{AT+B}\right) - 1}, \qquad (1)$$

where A, B and C are constants related to the properties of the IR thermometer, and c_2 is a universal constant with the value 14388 μm.K. Note that the value of T in equation (1) has the units of kelvin, which are related to the more commonly used degrees Celsius units by

$$T/\mathrm{K} = t/{^\circ}\mathrm{C} + 273.15 \,. \tag{2}$$

Thus, a room temperature of 20 °C corresponds to a temperature on the kelvin scale of 293.15 K.

The relationship represented by equation (1) is determined by the manufacturer of an IR thermometer, and is processed electronically inside the thermometer to produce a reading in degrees Celsius on the thermometer's display. This conversion of signal to temperature is, thus, hidden from the user and, in any case, is not usually of much interest to the user.

However, in order to calibrate an IR thermometer, the calibration laboratory *does* require knowledge of the details of this conversion process. (This is also true in many in-use measurement situations, but in-field use of IR thermometers is not covered in this guide.) The conversion from signal to temperature can be represented by the inverse of equation (1):

$$T = \frac{c_2}{A\ln(C/S+1)} - \frac{B}{A} \,. \tag{3}$$

Evaluation of equations (1) and (3) requires knowledge only of the thermometer parameters A and B. Because calibration of an IR thermometer involves the determination of temperature corrections, it turns out that the value of C is unimportant, as long as the same value is always used for all calculations. Therefore, we can simply assign $C = 1$ in the evaluation of equations (1) and (3). A and B are both related to the wavelength range over which the IR thermometer operates:

$$A = \lambda_0\left(1 - \frac{\Delta\lambda^2}{2\lambda_0^2}\right) \tag{4}$$

$$B = \frac{c_2\Delta\lambda^2}{24\lambda_0^2} \,, \tag{5}$$

where λ_0 is the centre wavelength of the range and $\Delta\lambda$ is the width of the wavelength range. Thus, for an IR thermometer operating from 8–14 μm, we get $\lambda_0 = 11$ μm and $\Delta\lambda = 6$ μm, and equations (4) and (5) give $A = 9.36$ μm and $B = 178$ μm.K, respectively.

We can illustrate the conversion of temperature to signal by using these values (along with $C = 1$) in equation (1). For example, for a temperature of 50 °C (323.15 K), equation (1) gives $S = 0.01132$. (Signal-to-temperature conversion can then be checked by using this value of S in equation (3) to re-calculate the value of $T = 323.15$ K.)

While many low-temperature IR thermometers operate over this wavelength range of 8–14 μm, there are many other ranges also in use, such as 8–13 μm and 7–18 μm. It is important to check the specifications to determine the actual wavelength range used.

Influences on the Readings of IR Thermometers

Emissivity

The intensity of the radiation emitted by an object depends not only on its temperature, but also on a property called emissivity. Emissivity is a number ranging from 0 to 1 that characterises how well an object emits radiation. An object with an emissivity of 1 is referred to as a blackbody (an idealised perfect emitter). An object with an emissivity of 0.8 emits 80% of the radiation that a blackbody does, an object with an emissivity of 0.5 emits 50% of a blackbody's radiation, and so on.

Instrumental Emissivity

Because of the influence of emissivity, different objects at the same temperature will produce different IR thermometer signals, and give correspondingly different readings. To account for this, IR thermometers have what is called an "instrumental emissivity" adjustment, which should be set by the user to the value of the emissivity of the target object's surface. On some thermometer models, the instrumental emissivity cannot be adjusted, but is fixed at a value of usually 0.95, but sometimes 0.97. These instruments have limited application.

Reflected Radiation

A further complication in IR thermometry measurements is that objects that are not blackbodies are partial reflectors of radiation. For any opaque object, the emissivity and reflectivity always sum to 1. Thus, an object with an emissivity of 0.8 has a reflectivity of 0.2. This means that 20% of all the radiation that is emitted from surrounding objects, and falls onto the target object, is reflected. This reflected radiation is detected by the IR thermometer and is added to the radiation emitted by the target object. Thus, the reading on the thermometer depends not only on the temperature of the target, but also on the temperature of its surroundings. Objects that are good emitters (those having an emissivity close to 1) tend to be black, and the higher the emissivity the lower the reflectivity and, therefore, the smaller the effect of the surroundings on the thermometer reading.

Detector Radiation

Finally, the detector itself also emits radiation. The signal at the detector's output corresponds to the difference between the in-coming radiation from the target (including reflected radiation) and the out-going radiation emitted by the detector. All low-cost IR thermometers use uncooled detectors, so the detector is at, or slightly above, room temperature. If the target is below about 200 °C then the radiation emitted by the detector is a significant fraction of the in-coming radiation and must be accounted for. Some IR thermometers use thermoelectric devices to cool the detector well below ambient. In these more expensive models, the detector radiation can normally be neglected for most target temperatures, but these instruments are not covered in this guide.

Measurement Equation

Including all of these effects – the emissivity of the target, the reflected radiation, and the radiation emitted by the detector – results in a measured signal, S_{meas}, at the output of the detector, given by a measurement equation that consists of the sum of three terms:

$$S_{\mathrm{meas}} = \varepsilon_{\mathrm{s}} S(T_{\mathrm{s}}) + (1-\varepsilon_{\mathrm{s}}) S(T_{\mathrm{w}}) - S(T_{\mathrm{d}}) \,, \tag{6}$$

where T_{s} is the temperature of the target (the quantity of interest), T_{w} is the temperature of the surroundings (often the walls of the room), T_{d} is the temperature of the detector, ε_{s} is the emissivity of the target's surface, and $1 - \varepsilon_{\mathrm{s}}$ is its reflectivity. Each of the three terms on the right-hand side of equation (6) corresponds to a different component of radiation: the first, $\varepsilon_{\mathrm{s}} S(T_{\mathrm{s}})$, corresponds to the radiation emitted by the target; the second, $(1 - \varepsilon_{\mathrm{s}})S(T_{\mathrm{w}})$, to the radiation reflected from the surroundings; and the third, $S(T_{\mathrm{d}})$, to the radiation emitted by the detector. Each of the $S(T)$ functions can be calculated by inserting the appropriate temperature value into equation (1), remembering to first convert any degrees Celsius temperatures into kelvin temperatures.

Processing the Measured Signal

If the measured signal, S_{meas}, given by equation (6) is substituted into the signal-to-temperature conversion equation (3), the result will not be the target temperature T_{s}, because of the influences of the target emissivity, the temperature of the surroundings, and the temperature of the detector (ε_{s}, T_{w}, and T_{d}). In order to produce a reading that better represents the target temperature, the IR thermometer pre-processes the measured signal before conversion to temperature, in effect applying corrections for the above influences. To do this reliably, the thermometer must somehow obtain values for the three influence variables, ε_{s}, T_{w}, and T_{d}.

The detector temperature, T_{d}, can be accurately determined by using an internal temperature probe mounted directly on the detector. Its measurement occurs automatically as part of the IR thermometer's measurement process and is completely hidden from the user.

For IR thermometers with an adjustable instrumental emissivity setting, $\varepsilon_{\mathrm{instr}}$, the user can inform the thermometer of the value of the target emissivity by setting $\varepsilon_{\mathrm{instr}}$ correctly. For fixed-emissivity instruments, the manufacturer designs the thermometer to carry out measurements only on specific objects (i.e., objects having a specific emissivity). Many food products, plastics, materials made from organic compounds (such as paper, wood, and skin), and most paints have emissivities close to 0.95 in the 8–14 μm range (i.e., they are almost black), so 0.95 is often chosen as the fixed instrumental emissivity setting.

Finally, the temperature of the surroundings, T_{w}, will depend on the measurement situation, and will vary from measurement to measurement. For this influence variable, most IR thermometer manufacturers make the implicit assumption that T_{w} will be approximately the same as the detector temperature, T_{d}. In other words, they assume that all measurements are to be performed in ambient surroundings. This assumption is usually fine during calibration in a well-controlled laboratory, but it can be quite misleading in other measurement situations. These include cool stores, where the temperature of the surroundings is well below the temperature of the thermometer, and situations where products to be measured are surrounded by hot objects, such as heaters, which are well above the temperature of the thermometer.

Armed with this information, the IR thermometer processes the measured signal as follows: first the measured signal is divided by the instrumental emissivity setting; then a quantity corresponding to the signal at the detector temperature is added (i.e., an amount given by equation (1) with $T = T_{\mathrm{d}}$ inserted); finally, the resulting signal value is converted to a measured temperature value, T_{meas}. This is represented mathematically as:

$$S(T_{\mathrm{meas}}) = \frac{S_{\mathrm{meas}}}{\varepsilon_{\mathrm{instr}}} + S(T_{\mathrm{d}}) \,. \tag{7}$$

Measurement Errors

What are the consequences of this signal processing? To answer this, we first substitute S_{meas} from equation (6) into equation (7):

$$S(T_{\mathrm{meas}}) = \frac{\varepsilon_{\mathrm{s}} S(T_{\mathrm{s}}) + (1-\varepsilon_{\mathrm{s}}) S(T_{\mathrm{w}}) - (1-\varepsilon_{\mathrm{instr}}) S(T_{\mathrm{d}})}{\varepsilon_{\mathrm{instr}}} \,. \tag{8}$$

We can rewrite this as the sum of three terms:

$$\begin{aligned} S(T_{\mathrm{meas}}) &= S(T_{\mathrm{s}}) \\ &\quad + \frac{(1-\varepsilon_{\mathrm{instr}})}{\varepsilon_{\mathrm{instr}}} \left[S(T_{\mathrm{w}}) - S(T_{\mathrm{d}}) \right] \\ &\quad + \frac{(\varepsilon_{\mathrm{s}} - \varepsilon_{\mathrm{instr}})}{\varepsilon_{\mathrm{instr}}} \left[S(T_{\mathrm{s}}) - S(T_{\mathrm{w}}) \right]. \end{aligned} \tag{9}$$

If the second and third terms (lines) of this equation are both zero, then the equation is simply $S(T_{\mathrm{meas}}) = S(T_{\mathrm{s}})$. This would imply that $T_{\mathrm{meas}} = T_{\mathrm{s}}$, that is, that the measured temperature is equal to the target temperature, which is what we are striving for. However, when either of the second or third lines of the equation is not zero, they represent error terms. In this case, the measured temperature is no longer equal to the target temperature.

The second line is zero when either $\varepsilon_{\mathrm{instr}} = 1$ or $T_{\mathrm{w}} = T_{\mathrm{d}}$. The condition $T_{\mathrm{w}} = T_{\mathrm{d}}$ is the manufacturers' assumption mentioned above. Equation (9) allows us to quantify the error when this condition doesn't hold. Setting $\varepsilon_{\mathrm{instr}} = 1$ (if possible) is often a good strategy because then the measured temperature, T_{meas}, is independent of T_{d}, as can be seen from both equations (8) and (9). However, this may introduce error through the third line in equation (9).

This third line is zero when either $\varepsilon_{\mathrm{instr}} = \varepsilon_{\mathrm{s}}$ or $T_{\mathrm{s}} = T_{\mathrm{w}}$, that is, when the instrumental emissivity matches the emissivity of the target, or the target temperature is the same as the temperature of the surroundings. Incorrectly setting the instrumental emissivity leads to an error that increases as the difference between these two temperatures increases. The user has no control over this error for fixed-emissivity instruments, unless the condition $T_{\mathrm{s}} = T_{\mathrm{w}}$ holds.

To summarise, it is only when $T_{\mathrm{w}} = T_{\mathrm{d}}$ and $\varepsilon_{\mathrm{instr}} = \varepsilon_{\mathrm{s}}$ that the reading on an IR thermometer will be equal to the true target temperature. If either of these conditions does not hold, then the thermometer reading will be in error. The only exception is when the target is a blackbody ($\varepsilon_{\mathrm{s}} = 1$), or blackbody conditions prevail ($T_{\mathrm{s}} = T_{\mathrm{w}}$), and the instrumental emissivity has been also set to 1, in which case the reading depends on neither T_{w} nor T_{d}.

Calibration

The errors discussed above occur in almost all measurements with IR thermometers, and care must be taken to ensure that these errors are not excessive. They also occur during calibration because the conditions for which the errors are zero ($T_w = T_d$ and $\varepsilon_{instr} = \varepsilon_s$) very rarely both hold. So how do we calibrate an IR thermometer when we expect errors in the readings, even for a perfect thermometer? The answer is that we must first calculate the expected readings for an ideal device under the calibration conditions and see how close the actual readings are to the expected ones. Or put another way, since we invariably use blackbodies to calibrate IR thermometers, we need to calculate "blackbody corrections", which we apply to our reference thermometer readings before comparing with the readings of the device under calibration.

Conventional blackbodies are made from cavities so that their effective emissivity is very close to 1 (see Figure 2). These blackbody cavities include purpose-built furnaces and inserts into dry-block calibrators. We can estimate the effective emissivity of a cavity, ε_{bb}, from its length L, the radius of its aperture, r, and the emissivity of the material from which it is made, ε_s:

$$\varepsilon_{bb} = 1-(1-\varepsilon_s)\left(\frac{r}{L}\right)^2 . \tag{10}$$

For example, a cavity made out of a material that has an emissivity of 0.9 (oxidised stainless steel), whose length is 150 mm and whose aperture radius is 25 mm, has an effective emissivity of:

$$\begin{aligned}\varepsilon_{bb} &= 1-(1-0.9)\left(\frac{25}{150}\right)^2 \\ &= 0.997.\end{aligned}$$

Plate-flat calibrators are also used as blackbody sources (see Figure 3). However, their emissivity is usually close to 0.95, so they are not true blackbodies. For the purpose of this guide, though, both types of calibration source will be referred to as blackbodies, and they will be distinguished by their effective emissivities.

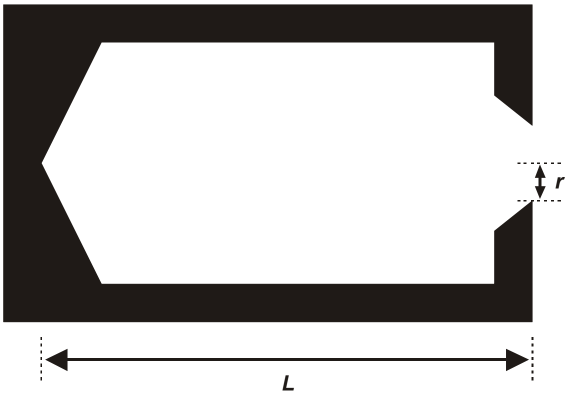

Figure 2. A blackbody cavity of length L and aperture radius r, whose walls have an emissivity ε_s. The effective emissivity of the cavity is given by equation (10). In use, the cavity is heated uniformly in a furnace or dry-block calibrator.

Figure 3. A flat-plate calibrator being viewed by an infrared thermometer. Photo courtesy of Fluke Corporation, Hart Scientific Division, reproduced with permission.

The reference thermometer, which measures the true temperature of the blackbody, can be either a contact thermometer, such as a platinum resistance thermometer, or a reference infrared thermometer. In the special case of the ice-point blackbody, no separate reference thermometer is required. These three methods of calibration are discussed below.

Contact Thermometer as Reference

When a contact thermometer is used as the reference, it is important that it is positioned in such a way that it measures the true temperature of the blackbody. This is especially important for flat-plate calibrators, where temperature gradients can lead to differences between the temperature of the plate where the IR thermometer under calibration is aimed and the temperature at the location of the reference thermometer (usually behind the surface of the plate).

In a calibration laboratory, the temperature of the surroundings is usually equal to ambient temperature, T_{amb}. Thus, we can rewrite equation (8) for the expected thermometer reading, T_{exp}, as:

$$S(T_{exp}) = \frac{\varepsilon_{bb}S(T_{ref}) + (1-\varepsilon_{bb})S(T_{amb}) - (1-\varepsilon_{instr})S(T_d)}{\varepsilon_{instr}} , \tag{11}$$

where ε_{bb} is the effective emissivity of the blackbody and T_{ref} is the true temperature of the blackbody, as determined by the reference thermometer. The second term in the numerator of equation (11) corresponds to ambient radiation that enters the blackbody cavity from the surroundings and finds its way back out, or the radiation that is reflected off the flat plate. For the case of the cavity, whose effective emissivity is generally very close to 1, this term will be very small.

For a given set of conditions, the expected temperature can be calculated by evaluating the right-hand side of equation (11) (with the aid of equation (1) to determine $S(T_{ref})$, $S(T_{amb})$, and $S(T_d)$), thus giving $S(T_{exp})$, then equation (3) can be used to extract T_{exp} from $S(T_{exp})$. The “blackbody correction”, ΔT_{bb}, is the difference between the expected reading and the reference thermometer’s reading:

$$\Delta T_{bb} = T_{exp} - T_{ref} \,. \qquad (12)$$

This blackbody correction can be added to the reference thermometer reading to give the expected IR thermometer reading. These calculations are easily performed in an Excel spreadsheet (see the file associated with this technical guide).

An example calculation is given in Table 1 for the calibration of an 8–14 μm IR thermometer whose instrumental emissivity is fixed at 0.95, using a blackbody cavity with an effective emissivity of 0.997. In the example, the ambient temperature is 20 °C and the detector temperature is 21 °C. Note that the detector temperature is not generally known, as it is not displayed on the device, so its value must be approximated, or guessed at, in order to calculate the blackbody corrections. The values in Table 1 provide a means for you to check the accuracy of your spreadsheets.

Figure 4 shows the blackbody corrections for the entire range of blackbody temperatures from –50 °C to 500 °C. Also shown is the effect of various detector temperatures. The detector temperature may differ from ambient if the thermometer has been stored in a room at a different temperature to the calibration laboratory and not given time to equilibrate before measurements are made. The detector may also become warmer than ambient if placed in front of a hot blackbody for a length of time. As Figure 4 shows, there is only a weak dependence of the blackbody correction on detector temperature, mainly at lower temperatures. The bulk of the correction is due to the fact that $\varepsilon_{instr} \neq \varepsilon_{bb}$.

If the instrumental emissivity is not fixed, then setting it to 1 removes any dependence of the reading on the detector temperature (see equation (11)). When the calibration is carried out using a blackbody cavity with an effective emissivity close to 1, then we should expect the blackbody corrections to be much smaller than those shown in Figure 4 because now $\varepsilon_{instr} \approx \varepsilon_{bb}$. This is indeed the case, as shown by the solid line in Figure 5. However, if the blackbody is a flat-plate calibrator with an emissivity of 0.95, then the larger blackbody corrections given by the dashed line in Figure 5 need to be applied. For a flat-plate blackbody, the blackbody corrections would be smaller if the instrumental emissivity were set to match ε_{bb}, i.e., $\varepsilon_{instr} = 0.95$. These corrections are shown in Figure 6. When the detector temperature also matches the ambient temperature, the corrections are all zero regardless of the blackbody temperature.

Table 1. Calculation of the blackbody corrections for three values of T_{ref} for an 8–14 μm IR thermometer (A = 9.36 μm, B = 178 μm.K) with $\varepsilon_{instr} = 0.95$, $\varepsilon_{bb} = 0.997$, T_{amb} = 20 °C, and T_d = 21 °C.

T_{ref} (°C)	$S(T_{ref})$ [eq (1)]	$S(T_{amb})$ [eq (1)]	$S(T_d)$ [eq (1)]	$S(T_{exp})$ [eq (11)]	T_{exp} (°C) [eq (3)]	ΔT_{bb} (°C) [eq (12)]
–50	0.00175	0.00732	0.00744	0.00147	–56.5	–6.5
100	0.02025	0.00732	0.00744	0.02088	103.0	3.0
500	0.16773	0.00732	0.00744	0.17566	516.4	16.4

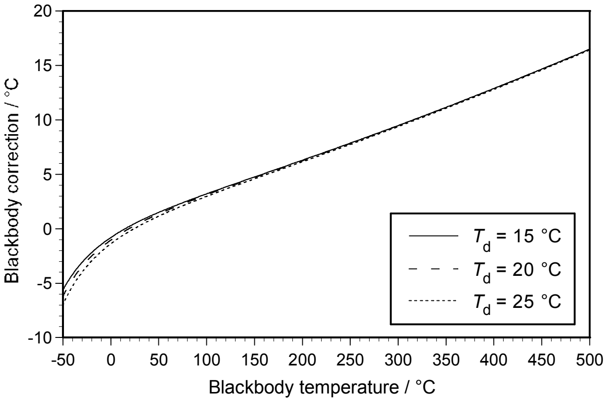

Figure 4. Corrections to the temperature of a blackbody calibration source, whose effective emissivity is $\varepsilon_{bb} = 0.997$, to give the expected reading for an 8–14 μm IR thermometer with a fixed emissivity of $\varepsilon_{instr} = 0.95$. The ambient temperature is assumed to be T_{amb} = 20 °C and the detector temperature is as given on the graph.

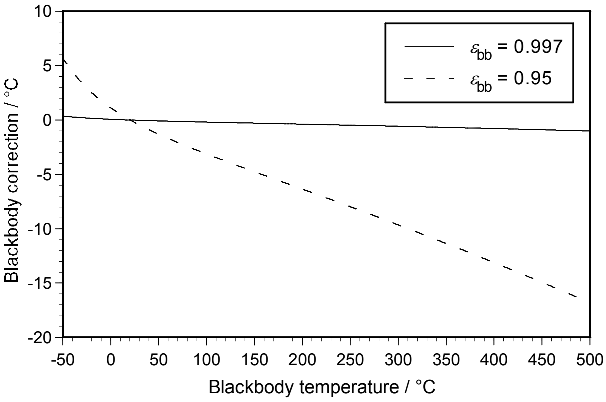

Figure 5. The solid line is for the same conditions as Figure 4, except that the emissivity setting on the IR thermometer is $\varepsilon_{instr} = 1$. The dashed line is for a flat-plate calibrator with emissivity of $\varepsilon_{bb} = 0.95$, again for $\varepsilon_{instr} = 1$. For both curves, the blackbody corrections are independent of the detector temperature.

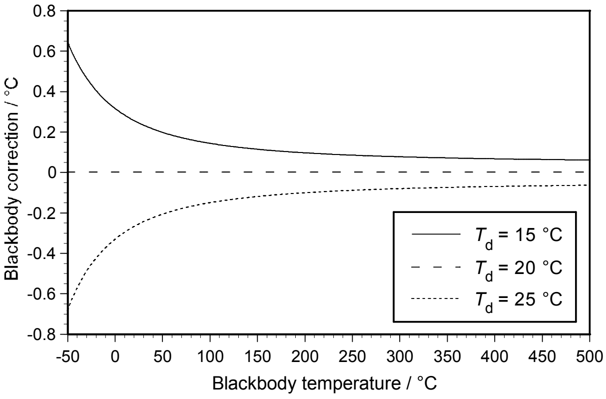

Figure 6. Same conditions as Figure 4, but for an IR thermometer with an emissivity setting of $\varepsilon_{instr} = 0.95$ viewing a flate-plate calibrator with emissivity of $\varepsilon_{bb} = 0.95$. When $T_d = T_{amb}$ = 20 °C, the blackbody corrections are zero for all temperatures.

The calibration procedure is summarised by the following steps:

1. Determine the minimum and maximum wavelengths for the operating wavelength range of the device under calibration. These should be stated in the thermometer's specifications under "spectral response".
2. Using these values in equations (4) and (5), calculate the *A* and *B* coefficients of the thermometer response function.
3. Determine the blackbody emissivity, $\varepsilon_{\mathrm{bb}}$, either as an effective value from equation (10) for a cavity, or directly from the specifications for a flat-plate calibrator.
4. Set the instrumental emissivity, $\varepsilon_{\mathrm{instr}}$, as close as possible to $\varepsilon_{\mathrm{bb}}$ (unless requested otherwise by the client), or if the instrumental emissivity is fixed, determine its value from the thermometer's specifications.
5. Measure the ambient temperature, T_{amb}, with an air-temperature probe.
6. Estimate the detector temperature, T_{d}. This is likely to be the same as ambient temperature provided the IR thermometer has had sufficient time to equilibrate with the calibration laboratory and if the IR thermometer is not heated excessively by radiation from the blackbody. If the instrumental emissivity is set to 1, the value of T_{d} is not required.
7. For each calibration point, read the reference thermometer, T_{ref}, and calculate the expected IR thermometer reading, T_{exp}, using equation (11). Compare the actual reading on the IR thermometer with the value of T_{exp}. The difference between the expected temperature and the actual reading is the correction that should be reported on the calibration certificate.

Infrared Thermometer as Reference

In some cases a separate IR thermometer is used as the reference device to measure the temperature of the blackbody calibration source. This reference IR thermometer must itself have already been calibrated. The blackbody corrections for this method of calibration differ to those given in the previous section.

Some flat-plate calibrators have their digital temperature readout adjusted by the manufacturer using an IR thermometer as the reference. This is often referred to as a "radiometric calibration" of the display. This takes into account the emissivity of the plate, ambient reflections, and the instrumental emissivity setting of the device under calibration (through a setting on the flat-plate controller). In effect, this type of calibrator automatically applies the corrections discussed in the previous section, and the reading on the display gives the expected reading of the device under calibration. However, care must be taken when using this display as the reference temperature, as the conditions under which it was calibrated may differ from those present when the plate is used as a calibration source. In particular, the ambient temperature may not be the same (causing the reflected radiation to be different), the temperature of the detector of the device under calibration may differ from ambient, and the reference thermometer's wavelength range may be different from that of the device under calibration. Normally, the specified uncertainty for the calibrator will include a component to account for modest variations in ambient and detector temperatures. The user should check that the operating wavelength ranges match.

In this section, we assume that the readings of the reference IR thermometer are made at the same time as the measurements of the device under calibration, so that the ambient conditions during a sequence of measurements are identical. We also assume that the instrumental emissivity setting on the reference thermometer is 1, so that its readings are independent of the temperature of its detector. Finally, it is also assumed that the operating wavelength range of the reference thermometer is the same as that of the device under calibration (the *A* and *B* values are the same for both instruments). If this latter condition doesn't hold, then the calculation of the blackbody corrections is more complicated and requires additional information.

Applying equation (8) to both the reference thermometer and the thermometer under calibration, and determining the difference in measured signals, gives:

$$S(T_{\mathrm{exp}}) = S(T_{\mathrm{ref}}) + \frac{(1-\varepsilon_{\mathrm{instr}})}{\varepsilon_{\mathrm{instr}}}\left[S(T_{\mathrm{ref}}) - S(T_{\mathrm{d}})\right]. \qquad (13)$$

As before, T_{exp} is the expected reading for the device under calibration, $\varepsilon_{\mathrm{instr}}$ is its instrumental emissivity setting, and T_{d} is the temperature of its detector. T_{ref} is the reading on the reference thermometer (which is generally not equal to the temperature of the blackbody, particularly when a flat plate is used). The blackbody corrections are, again, given by $\Delta T_{\mathrm{bb}} = T_{\mathrm{exp}} - T_{\mathrm{ref}}$. Notice that equation (13) does not depend on the true temperature of the blackbody, or on the value of its effective emissivity, or on the ambient temperature. The fact that these values do not need to be known is a major advantage of this method. Additionally, when $\varepsilon_{\mathrm{instr}} = 1$, the blackbody corrections are zero for all temperatures. This is contrasted with equation (11) where, under this condition, the blackbody corrections still depend on ambient temperature and the effective emissivity of the blackbody.

Figure 7 gives the blackbody corrections for this method for a range of instrumental emissivity settings on the device under calibration, as a function of the reference thermometer reading. The temperature of the detector of the device under calibration is assumed to be $T_{\mathrm{d}} = 20$ °C. Although not shown, the variation of the corrections with changes in detector temperature is approximately the same as that shown in Figure 4.

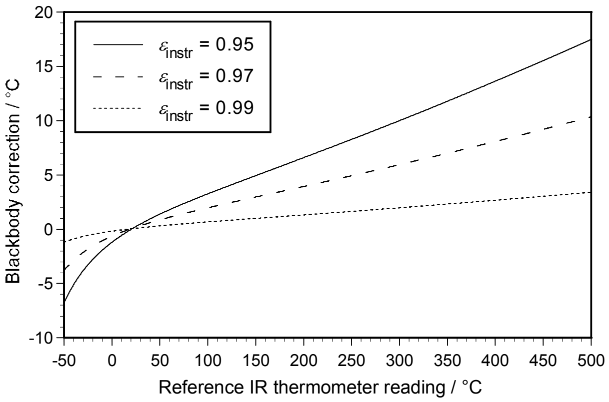

Figure 7. Corrections required to the readings of a reference IR thermometer aimed at a blackbody calibration source when calibrating an 8–14 μm IR thermometer with a detector temperature of $T_{\mathrm{d}} = 20$ °C and with instrumental emissivity as given on the graph. The reference thermometer also operates from 8–14 μm and its instrumental emissivity is set to 1.

The calibration procedure when an IR thermometer is used as the reference is summarised as follows:

1. Determine the minimum and maximum wavelengths for the operating wavelength range of the device under calibration. These should be stated in the thermometer's specifications under "spectral response".
2. Check that these minimum and maximum wavelengths are the same for the reference IR thermometer.
3. Using these values in equations (4) and (5), calculate the *A* and *B* coefficients of the thermometer response function (which apply to both thermometers).
4. Set the instrumental emissivity, $\varepsilon_{\text{instr}}$, on the device under calibration as close to 1 as possible (unless requested otherwise by the client), or if the instrumental emissivity is fixed, determine its value from the thermometer's specifications.
5. Set the instrumental emissivity on the reference IR thermometer to 1.
6. Estimate the detector temperature, T_d, for the device under calibration. This is likely to be the same as ambient temperature provided the device under calibration has had sufficient time to equilibrate with the calibration laboratory and if the device under calibration is not heated excessively by radiation from the blackbody. If its instrumental emissivity is set to 1, the value of T_d is not required.
7. For each calibration point, read the reference IR thermometer, T_{ref}, and calculate the expected reading, T_{exp}, of the device under calibration using equation (13). Compare the actual reading on the device under calibration with the value of T_{exp}. The difference between the expected temperature and the actual reading is the correction that should be reported on the calibration certificate.

Ice Point as Reference

The ice point is an accurate and reliable reference temperature suitable for checking the accuracy and drift over time of IR thermometers. Since the emissivity of ice is $\varepsilon_\text{s} = 0.96$ in the infrared part of the spectrum, a good blackbody cavity, with an effective emissivity close to 1 (according to equation (10)), can easily be constructed using shaved ice (see [1]). Because the temperature of a properly constructed ice-point is defined to be precisely 0 °C, no reference thermometer is required for a calibration at this temperature.

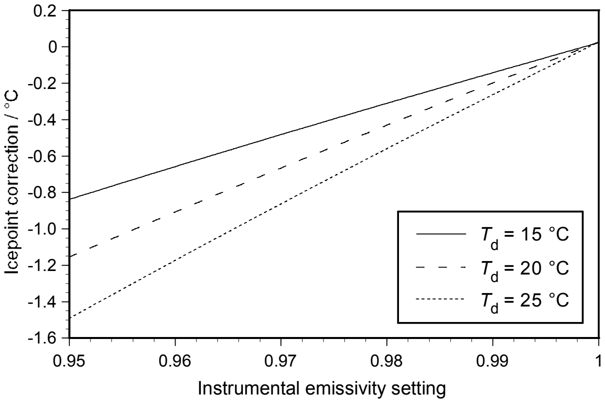

Figure 8. Expected reading for an 8–14 μm IR thermometer as a function of instrumental emissivity setting when viewing an ice-point blackbody cavity with effective emissivity of $\varepsilon_{\text{bb}} = 0.999$. The ambient temperature is $T_{\text{amb}} = 20$ °C.

To determine the expected reading on an IR thermometer when aimed at an ice-point blackbody, we can insert the value $T_{\text{ref}} = 0$ °C into equation (11). In this case, the blackbody correction is the same as the expected reading when expressed in degrees Celsius. Figure 8 shows the blackbody correction as a function of the instrumental emissivity setting on the device under calibration for three different detector temperatures, assuming that the ambient temperature is $T_{\text{amb}} = 20$ °C and the effective emissivity of the ice-point blackbody cavity is $\varepsilon_{\text{bb}} = 0.999$.

The calibration procedure for the ice-point calibration is identical to that for the contact thermometer as reference, except that in step 7 there is no reference thermometer to read; instead a single reference temperature of $T_{\text{ref}} = 0$ °C is used in equation (11).

Detector Temperature

A point of difficulty throughout this guide is that the value of T_d is not known to the user. It is measured internally by the instrument, but is not displayed on the readout. The best assumption is that T_d will be the same as, or close to, ambient temperature, and this may require some conditioning of the instrument before use. However, there are some situations where ensuring that $T_\text{d} = T_{\text{amb}}$ is not practicable. One is where the IR thermometer is used for an extended period in front of a hot source (e.g., during calibration at high temperatures), where the radiation from the source may heat the detector above ambient. The second is where the IR thermometer is used inside a walk-in freezer, where the ambient temperature is well below the specified operating temperature for the thermometer. In this case, the thermometer can still be used successfully, but the detector must be maintained above, usually, 0 °C.

Dependence on the detector temperature is removed if the instrumental emissivity is set to 1 (this is precluded in fixed-emissivity instruments). On the other hand, relatively large errors in the estimate (guess) of the detector temperature can usually be tolerated without significant error in the reading.

For adjustable-emissivity instruments, the detector temperature can, in fact, be inferred from two measurements of the same target using two different instrumental emissivity settings. The temperature and emissivity of the target, and the ambient temperature, do not need to be known. All that is required is that these values are constant during the two measurements. The detector temperature, T_d, can be calculated from the equation:

$$S(T_\text{d}) = \frac{\varepsilon_{\text{instr1}} S(T_{\text{meas1}}) - \varepsilon_{\text{instr2}} S(T_{\text{meas2}})}{\varepsilon_{\text{instr1}} - \varepsilon_{\text{instr2}}}, \qquad (14)$$

where T_{meas1} and T_{meas2} are the two IR thermometer readings when the instrumental emissivity is set to $\varepsilon_{\text{instr1}}$ and $\varepsilon_{\text{instr2}}$, respectively. The accuracy of calculations made with equation (14) is best when $\varepsilon_{\text{instr1}}$ and $\varepsilon_{\text{instr2}}$ are widely spaced; values of 0.5 and 1 are usually adequate. For example, two readings of a blackbody using an 8–14 μm thermometer might be $T_{\text{meas1}} = 141.8$ °C when the instrumental emissivity is set to $\varepsilon_{\text{instr1}} = 1$, and $T_{\text{meas2}} = 219.4$ °C when $\varepsilon_{\text{instr2}} = 0.5$. Substituting these values into equation (14) gives $T_\text{d} = 21.5$ °C.

Calculations of this sort are useful for determining the expected variation of detector temperature as the conditions inside the laboratory change. While it is not possible to do this for fixed-emissivity instruments, it may be possible to infer their behaviour from measurements made with similar adjustable-emissivity instruments.

Conclusion

Because low-temperature IR thermometers are designed to automatically overcome the problem of reflected radiation when used to carry out temperature measurements, calibration of such devices is not a straightforward task. Procedures for calibrating IR thermometers need to be carefully designed to take into account the instrumental emissivity setting on the device, its detector temperature, and ambient temperature, as well as the properties of the blackbody calibration source and the reference thermometer.

The methods given in this technical guide allow the calibration laboratory to calculate the expected reading for an ideal device, or the correction to the reference thermometer reading (the "blackbody correction"), against which the reading on the device under calibration should be compared. A calibration certificate should state the device corrections with respect to these expected readings, not with respect to the reference thermometer readings. For example, referring to Figure 8, an 8–14 μm thermometer with an instrumental emissivity of 0.95 is expected to read –1.2 °C (for detector and ambient temperatures both equal to 20 °C). If the actual reading was –0.9 °C, then the reported correction for this reading would be –0.3 °C. The certificate should also state the instrumental emissivity setting.

It should be stressed that the calibration is designed only to determine how well the thermometer conforms to its expected behaviour (i.e., how well T_{meas} conforms to equation (8)). In use, it is the responsibility of the user to ensure that the measurement conditions are such that the value of T_{meas} (after applying any certificate corrections) is a good approximation to T_{s}, the true temperature of the target. The necessary conditions are that both $\varepsilon_{\text{instr}} = \varepsilon_{\text{s}}$ and $T_{\text{d}} = T_{\text{w}}$ hold. That is, the instrumental emissivity must be set to the emissivity of the target and the detector temperature must equal the temperature of the surroundings. When either, or both, of these conditions does not hold, then the resulting error must be calculated using equation (9). Examples of these calculations are given in [2] and [3].

References

[1] MSL Technical Guide 2: "Infrared Thermometry Ice Point", http://msl.irl.cri.nz.

[2] P Saunders, "Reflection errors for low-temperature radiation thermometers", in *Proceedings of TEMPMEKO 2001, 8th International Symposium on Temperature and Thermal Measurements in Industry and Science*, edited by B Fellmuth, J Seidel, G Scholz, VDE Verlag GmbH, Berlin, 149–154, 2002.

[3] P Saunders, "Calibration and use of low-temperature direct-reading radiation thermometers", *Measurement Science and Technology*, **20**, 025104, 2009.

Prepared by Peter Saunders, June 2009.