3.2 Spectral-Band Thermometers

Spectral-band thermometers are by far the most common type of radiation thermometer. They are called spectral-band because they measure radiance over a specified band of wavelengths, normally a relatively narrow band centered somewhere in the range 0.5 μm to 20 μm. The spectral band is determined by a combination of the spectral transmission characteristics of the optical components in the thermometer, including any lenses, filters and windows, and by the spectral response of the detector. For very narrow-band instruments, mainly used as reference thermometers, the spectral band is almost solely defined by a single interference filter.

3.2.1 Spectral responsivity

The overall wavelength response characteristic of a radiation thermometer is known as its *spectral responsivity*. The center wavelength of the spectral responsivity is chosen largely according to the required temperature range of the thermometer, as guided by Wien's displacement law (Equation (2.2)). However, there are other considerations affecting the choice of wavelength, which will be discussed in later sections. The bandwidth is also dictated by temperature. Generally, thermometers measuring lower temperatures require wider bandwidths than those measuring higher temperatures to ensure that sufficient flux reaches the detector. Again, there are other considerations that have a bearing on the bandwidth, such as the presence of atomic and molecular absorption lines.

An example of the spectral responsivity of an industrial radiation thermometer commonly used in high-temperature furnaces is illustrated in Figure 3.1. For this thermometer the center wavelength is close to 1 μm and the bandwidth is approximately 0.1 μm. The spectral band is primarily determined by the combination of a glass filter (long pass filter) defining the short wavelength cut-off, and the responsivity of a silicon

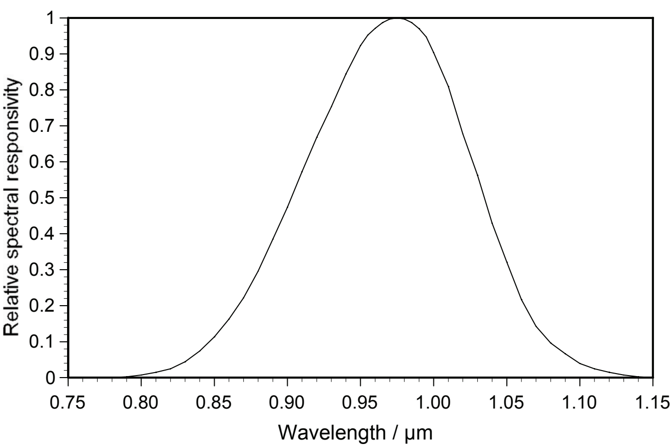

Figure 3.1. Relative spectral responsivity of an industrial radiation thermometer commonly used for furnace tube temperature measurement.

detector defining the long wavelength cut-off. The specified temperature range of this thermometer is 600 °C to 3000 °C.

3.2.2 Output signal

A simplified schematic of a spectral-band thermometer is shown in Figure 3.2. The operating principles are relatively straightforward. Radiation from the target is collected by a lens, then passed through a filter to select the appropriate wavelengths, and finally measured by a detector and signal processing system. In practice, the lens may be omitted, generally resulting in a larger and less well-defined field of view, or it may be replaced by a system of lenses or mirrors.

There are always two principal apertures in the optical system of a radiation thermometer. The *target-defining aperture* (also called the *field stop*) defines the field of view—the area on the target from which radiation is measured. The *solid-angle-defining aperture* (or *aperture stop*) determines the angular acceptance of the thermometer—the cone of rays from the target that is intercepted by the thermometer (this is similar to the *f*-stop in a camera). The lens in Figure 3.2 focuses these rays onto the target-defining aperture, and these rays then fall onto the detector. A photograph of a typical spectral-band thermometer is shown in Figure 3.3.

The measured signal at the output of the detector, S_m, is given by the integral of the radiance of the target (Equation (2.11), in the absence of reflections) over the spectral responsivity of the thermometer:

$$S_{\mathrm{m}} = k\int_0^\infty s(\lambda)\varepsilon(\lambda)L_{\mathrm{b}}(\lambda,T)d\lambda\,. \tag{3.1}$$

In this equation, $s(\lambda)$ is the relative spectral responsivity (the peak can be arbitrarily chosen to be 1, as in Figure 3.1), and k is a constant dependent on the dimensions of the apertures, the absolute transmission of the optical components, and the response of the detector. In practice, the value of k is determined through calibration using a blackbody source, for which $\varepsilon(\lambda) = 1$, and the signal processing system inside the thermometer infers the value of T for a given measured signal. Thus, the implementation of Equation (3.1) is

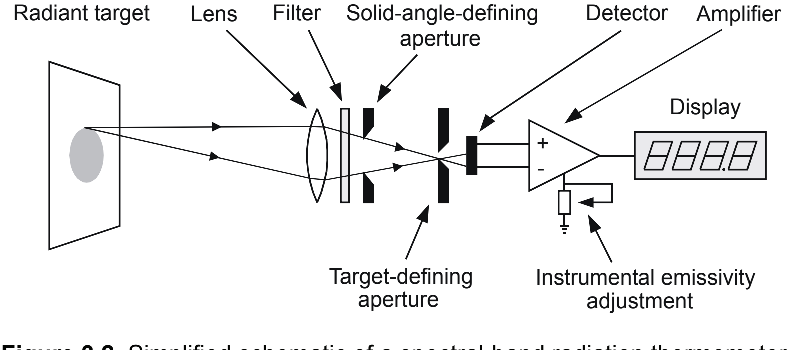

Figure 3.2. Simplified schematic of a spectral-band radiation thermometer.

Figure 3.3. Photograph of an industrial spectral-band radiation thermometer.

generally hidden from the user of industrial radiation thermometers. However, to allow us to sensibly analyze the errors and uncertainties inherent in radiation thermometry, we need to understand this relationship between measured signal and temperature.

3.2.3 Monochromatic approximation

Although Equation (3.1) looks overly complicated, for analysis in most industrial applications it can be much simplified. When the bandwidth is sufficiently narrow and/or the accuracy requirements are not too great, we can replace the integral in Equation (3.1) by the integrand evaluated at a single wavelength:

$$S_{\mathrm{m}} = k\varepsilon(\lambda)L_{\mathrm{b}}(\lambda, T)\,, \tag{3.2}$$

where the wavelength λ can be approximated as the center wavelength of the spectral responsivity, and k is again a constant but with a different value to that in Equation (3.1) and is proportional to the thermometer's bandwidth. This is the so-called *monochromatic approximation*, which simply states that the measured signal is proportional to the spectral radiance of the target.

Because radiation thermometers are calibrated against blackbodies (see Chapter 6), the thermometer in effect assumes that the target is a blackbody. Thus, the indicated temperature, T_m, is internally calculated from the measured signal, S_m, by a similar expression to (3.2) but with the emissivity equal to 1:

$$kL_b(\lambda, T_m) = S_m \,. \tag{3.3}$$

Equating equations (3.2) and (3.3) allows us to relate the temperature reading, T_m, to the temperature of the target, T, without needing to know the value of k:

$$L_b(\lambda, T_m) = \varepsilon(\lambda) L_b(\lambda, T) \,. \tag{3.4}$$

The thermometer itself, of course, does need to know the value of k in order to carry out the calculation indicated in Equation (3.3), but the operating wavelength, λ, is the only thermometer property that *we* require in order to determine the relationship between the measured temperature and the true temperature.

Assuming that the emissivity doesn't vary over the bandwidth of the thermometer, we can write Equation (3.4) more generally as

$$S(T_m) = \varepsilon(\lambda) S(T) \,, \tag{3.5}$$

where $S(T)$ is the internal function used by the thermometer to convert between signal and temperature. In the monochromatic approximation, this has the form

$$S(T) = \left[\exp\left(\frac{c_2}{\lambda T} \right) - 1 \right]^{-1} \approx \exp\left(\frac{-c_2}{\lambda T} \right) , \tag{3.6}$$

where a proportionality constant multiplying the right-hand of Equation (3.6) has been taken to be 1, and the expression after the ≈ symbol arises from Wien's approximation to Planck's law. Inverting Equation (3.6) allows T to be calculated from a given value of S:

$$T = \frac{c_2}{\lambda \ln\left(\frac{1}{S} + 1 \right)} \approx \frac{-c_2}{\lambda \ln(S)} \,. \tag{3.7}$$

The monochromatic approximation will be used largely throughout this book, as the errors introduced by this approximation are usually negligible compared to other errors encountered in industrial applications. Situations where consideration of the bandwidth of the spectral responsivity is important will be explicitly noted.

Any error, ΔS, in the measured signal will lead to an error, ΔT, in the temperature determined from Equation (3.7). In the Wien approximation, the relationship between the signal and temperature errors can be written as

$$\Delta T = \frac{\lambda T^2}{c_2}\frac{\Delta S}{S}. \tag{3.8}$$

Thus, the error increases linearly with increasing wavelength and also with the square of the temperature. This error equation will be compared to the corresponding equations for ratio and multi-wavelength thermometers in Sections 3.6 and 3.7, respectively.

3.2.4 Radiance temperature

The measured temperature, T_m, appearing in Equation (3.5), determined directly from the signal measured by the thermometer, is referred to as the *radiance temperature*, T_λ, of the target. Radiance temperature is a useful concept and will be exploited throughout this book. It is equal to the temperature of a blackbody having the same spectral radiance as a real target. Using the Wien approximation to Equation (3.6), the true target temperature, T, can be estimated from the radiance temperature through the equation

$$\frac{1}{T} = \frac{1}{T_\lambda} + \frac{\lambda}{c_2}\ln\left[\varepsilon(\lambda)\right]. \tag{3.9}$$

This is just another way of writing Equation (3.4).

Note that the radiance temperature depends on wavelength, so that radiation thermometers operating at different wavelengths will measure different radiance temperatures for the same target, even if the target is a graybody (a graybody has the same emissivity at all wavelengths). The only exception is when the target is a blackbody, i.e., $\varepsilon(\lambda) = 1 \Rightarrow \ln\left[\varepsilon(\lambda)\right] = 0$, in which case the radiance temperature is independent of wavelength and is equal to the true temperature.

To illustrate the variation of radiance temperature with wavelength, imagine a freely radiating graybody object with an emissivity of 0.85 at a temperature of 900 °C (recall that freely radiating means there are no nearby objects; i.e., no reflection errors). Equation (3.9) tells us that a spectral-band thermometer operating at 1 μm will measure a radiance temperature of 885 °C and that a 3.9 μm thermometer will measure 842 °C. For both thermometers the radiance temperature is lower than the true temperature, as expected since our target is radiating less than a blackbody, with the error being larger for the longer-wavelength thermometer.

3.2.5 Instrumental emissivity

As illustrated by the numerical example above, because equations (3.5) and (3.9) contain the value of the emissivity, the radiance temperature, T_λ, does not equal the true temperature of the target, T, unless the target is a blackbody. To overcome this problem, most industrial radiation thermometers have a built-in adjustment called the *instrumental* *emissivity*, $\varepsilon_{\text{instr}}$, which is designed to compensate for the target's emissivity. The signal from the target (the right-hand side of Equation (3.5)) is first internally divided by the value of $\varepsilon_{\text{instr}}$ set by the user:

$$S(T_{\text{m}}) = \frac{\varepsilon(\lambda)S(T)}{\varepsilon_{\text{instr}}}, \tag{3.10}$$

and then Equation (3.7) is used to calculate the reading T_{m} from $S(T_{\text{m}})$. Clearly, if the user sets $\varepsilon_{\text{instr}}$ to be equal to $\varepsilon(\lambda)$ then $S(T_{\text{m}}) = S(T)$ so that $T_{\text{m}} = T$. When the instrumental emissivity adjustment is implemented (i.e., set to a value other than 1.00), the thermometer reading no longer equals the radiance temperature. In fact, we can make the general definition that *the radiance temperature equals the reading on the thermometer when the instrumental emissivity is set to 1.00.*

The instrumental emissivity adjustment often takes the form of a digital input that can be set from 0.10 and 1.00, often in steps of 0.01. Sometimes, however, the adjustment is an analogue dial, and in other cases the instrumental emissivity is fixed at a value such as 0.95. For serious measurements, these fixed-emissivity instruments should be avoided (unless the emissivity is fixed to a value of 1.00).

Referring back to the numerical example at the end of the previous section, the errors in measuring the freely radiating object for both the 1 μm and 3.9 μm thermometers would be reduced to zero if the instrumental emissivity were set to 0.85. While this technique of eliminating the error in the reading is often the advice of radiation thermometer manufacturers, and in this example is indeed the correction solution, in practice it is very rare to find a freely radiating target. Reflections from surrounding objects completely change the nature of the problem, often causing a significant increase in the radiance temperature of the target. In these situations, equations (3.9) and (3.10) do not hold unless we replace $\varepsilon(\lambda)$ by an effective emissivity, which must be determined for each particular measurement geometry and surrounding temperature distribution. In some cases, the instrumental emissivity adjustment can be used to eliminate the additional errors. Effective emissivity is discussed in more detail in Section 4.3.4.

3.3 The Gold-Cup Pyrometer

The gold-cup pyrometer [10] is a special type of radiation thermometer that is used essentially as a contact thermometer. It is comprised of a gold-plated hemisphere (or cup) containing a small quartz window through which radiation from a surface passes onto a detector (see Figure 3.4). When the hemisphere is placed against the surface to be measured, it (together with the surface) forms a blackbody cavity (see Section 6.2) so that the radiation passing through the window is independent of the emissivity of the surface. The hemisphere also serves to block out radiation falling onto the surface from the surroundings, thereby eliminating reflection errors.

While these features seem ideally suited for carrying out surface temperature measurement, there are several practical difficulties associated with the use of a gold-cup pyrometer for measuring furnace tube temperatures. The most obvious of these is that

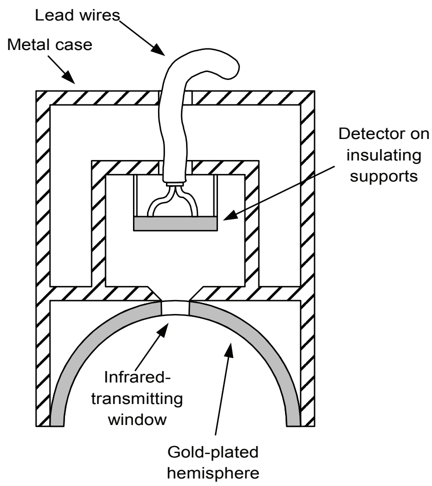

Figure 3.4. Schematic of the head of a gold-cup pyrometer.

because the cup must be placed on or very close to the radiating surface, only tubes within easy assess of the sight doors are able to be measured. The measuring head shown in Figure 3.4 is usually mounted on the end of a steel tube, which is inserted through the open sight door. Practicalities limit the overall length to about 3 m to 4 m, so that only tubes within this range can be measured.

Plastic and rubber components within the head, as well as the detector itself, must be maintained below about 65 °C for reliable operation. This means either that the instrument can only be used intermittently, for periods of about 2 to 6 seconds at a time, or that water cooling must be used to keep the head temperature down. The latter solution makes for a very cumbersome instrument. Furthermore, if the quartz window is cooled too much, there is a possibility that water vapor from the flue gas may condense on it, reducing the amount of radiation falling on the detector. Thus, the cup must be operated over a relatively narrow temperature range. The hot flue gas components in a furnace very quickly tarnish the gold surface of the cup. This reduces the normally high reflectance of the gold, which is required for the hemisphere/target surface to form a blackbody at the temperature of the target.

There are two broad categories of gold-cup pyrometer, designed for measurements above and below 500 °C, respectively. The high-temperature gold-cup pyrometer has a detector/filter combination similar to a spectral-band thermometer, so the signal response has the same form:

$$S(T) = \varepsilon_{\text{eff}}\, g \exp\left(\frac{-c_2}{\lambda T}\right), \tag{3.11}$$

where g is a constant and ε_{eff} is the *effective emissivity* of the cavity formed by the cup and the target's surface. For the low-temperature gold-cup pyrometer, filters are not normally used to restrict the bandwidth, so the signal response is very broadband and approximately follows the Stefan-Boltzmann law (Equation (2.8)):

$$S(T) = \varepsilon_{\text{eff}} g \left(T^4 - T_0^4 \right), \tag{3.12}$$

where g is again a constant and T_0 is the temperature of the detector. The low-temperature gold-cup pyrometer is not suitable for temperature measurement in petrochemical furnaces, so it won't be discussed further.

The effective emissivity in equations (3.11) and (3.12) is approximately given by

$$\varepsilon_{\text{eff}} = \frac{\varepsilon}{1-\rho_{\text{g}}(1-\varepsilon)} = 1 - \frac{(1-\rho_{\text{g}})(1-\varepsilon)}{1-\rho_{\text{g}}(1-\varepsilon)}, \tag{3.13}$$

where ε is the emissivity of the target and ρ_{g} is the reflectance of the gold. The expression after the second equals sign highlights the existence of two ideal conditions: (i) if gold were a perfect reflector ($\rho_{\text{g}} = 1$), the effective emissivity of the cavity would be $\varepsilon_{\text{eff}} = 1$, irrespective of the emissivity of the target; and (ii) if the target were a blackbody ($\varepsilon = 1$) then again the effective emissivity of the cavity would be $\varepsilon_{\text{eff}} = 1$, irrespective of the reflectance of the gold. For these two conditions, the signal given by Equation (3.11) depends only on the temperature of the target. In practice, the target would rarely be a blackbody, and even in good condition, gold has a reflectance no greater than 0.98 in the infrared. Thus, the measured signal always has a slight target-emissivity dependence.

Furthermore, as the gold tarnishes and its reflectance decreases, the effective emissivity becomes increasingly dependent on the target emissivity, as shown in Table 3.1. Assuming that the gold-cup pyrometer has been calibrated with respect to a blackbody (see Chapter 6), the error, ΔT, in the temperature measured by the gold-cup pyrometer as a function of ε_{eff} is approximately given by

Table 3.1. Effective emissivity of a gold-cup pyrometer, given by Equation (3.13), as a function of the reflectance of the gold surface, ρ_{g}, and the emissivity of the target, ε.

ρ_{g}	$\varepsilon = 0.80$	$\varepsilon = 0.85$	$\varepsilon = 0.90$	$\varepsilon = 0.95$
0.95	0.988	0.991	0.994	0.997
0.90	0.976	0.983	0.989	0.995
0.85	0.964	0.974	0.984	0.992
0.80	0.952	0.966	0.978	0.990
0.75	0.941	0.958	0.973	0.987
0.70	0.930	0.950	0.968	0.984
0.65	0.920	0.942	0.963	0.982
0.60	0.909	0.934	0.957	0.979

$$\Delta T = -\frac{(1-\varepsilon_{\text{eff}})\lambda T^2}{c_2}, \tag{3.14}$$

where T is the target temperature in kelvin. For a tube with an emissivity of 0.85 at a temperature of 900 °C, a gold-cup pyrometer operating at 1 μm will read low by about 6 °C if the reflectance of the gold has been degraded to a value of 0.6. Note that this error would not be apparent by recalibrating the gold-cup pyrometer against a blackbody because $\varepsilon_{\text{eff}} = 1$ for a blackbody target regardless of the reflectance of the gold.

Perhaps the most problematic aspect of the gold-cup pyrometer is that its very use alters the radiant conditions of the target, resulting in a change in the target temperature. Under normal operation, a furnace tube receives radiation from its surroundings. This heat is conducted through the tube wall and into the product being heated. Placing a gold-cup pyrometer onto the tube's surface shields the tube, leading to a decrease in the temperature of that part of the tube. The rate of cooling depends on the radiant conditions in the furnace and on the thermal conductivity of the tube material, and can be as much as several degrees Celsius per second.

The best way to overcome this problem is to log the readings from the gold-cup pyrometer as a function of time as the instrument is moved into the furnace and contacted with the tube. From a plot of the readings it is a reasonably simple matter to determine the temperature of the tube at the time of first contact. A typical plot is shown in Figure 3.5. In the region marked A the gold cup is being moved towards the tube. In this region it is behaving in a similar manner to a normal spectral-band thermometer, in that the signal is comprised of components due to emission of radiation from the tube and reflection of radiation from the surroundings. In the region marked B the gold cup is close enough to the tube that part of the reflected radiation is obscured. As the gold cup gets closer and closer to the tube the obscuration gets larger and larger, until at point C the gold cup makes contact with the tube and all of the reflected radiation is obscured. This point

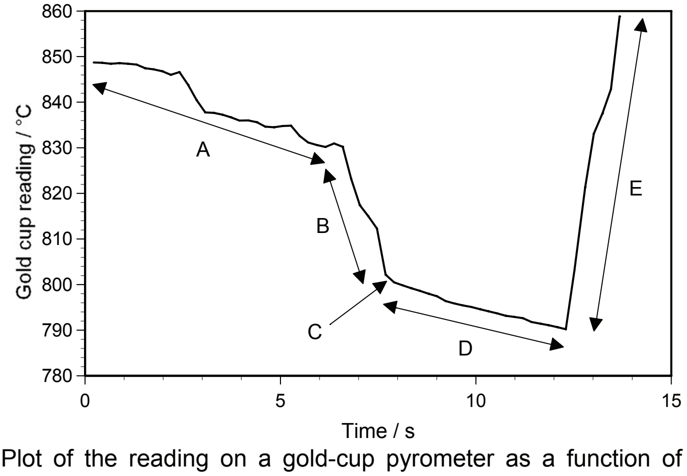

Figure 3.5. Plot of the reading on a gold-cup pyrometer as a function of time as it is moved into a furnace towards a tube, where first contact is made at point C.

represents the temperature of interest. In region D the tube cools due to the absence of incident radiation, and in region E the gold cup is withdrawn.

Although not particularly suited for everyday use, if operated with care, the gold-cup pyrometer can serve as a reference instrument against which to check measurements made with a spectral-band thermometer. This is particularly important in validating the methods used to correct spectral-band thermometer readings for the effects of reflected radiation and absorption and emission by the flue gas (see Chapter 4).

3.4 Thermal Imagers

Thermal imagers are in most respects the same as spectral-band thermometers, except that they create a 2D temperature image of the target. This process is sometimes referred to as *thermography*. Thermal imagers are based on either *scanning systems* or *focal plane arrays*.

The older-style scanning systems use a single detector and a pair of rotating prisms or mirrors to generate an *x-y* scan of the target area. Alternatively, they may have a linear detector array defining one dimension and a single scanning prism or mirror to generate the other.

Almost all modern thermal imaging systems incorporate focal plane arrays. These consist of a 2D array of detectors in the image plane of the optical system. These may be photovoltaic or photoconductive detectors, or *charge-coupled devices* (CCDs). CCD technology has improved rapidly in recent years due to the popularity and convenience of CCDs in amateur astronomy and digital photography.

Thermal images are interpreted either qualitatively or quantitatively. Qualitative images are generally used diagnostically for energy management purposes and electrical fault finding. In these images absolute temperature values or absolute temperature differences are not important, but rather the thermal patterns in the images provide information on, for example, heat leaks in external walls of buildings, wet insulation inside walls, short circuits in electrical components, and so on.

Quantitative imaging is more demanding and requires that each pixel in the image be calibrated to represent the radiance temperature of the corresponding point on the target [11]. The process of calibrating each pixel of a thermal imager is essentially the same as calibrating a spectral-band thermometer (see Chapter 6), with the main difference being that thermal imagers require large-area blackbody cavities in order to fill the whole field of view. Generally, only the central region of the image is calibrated and correction factors may be determined to apply to pixels outside the central region. The sources of error that are discussed in Chapter 4 with respect to spectral-band thermometers all apply also to thermal imagers. However, in some cases, such as the size-of-source effect, the errors for thermal imagers are much worse.

Thermal imagers are becoming increasingly important in furnace tube temperature measurement, for the principal reason that they significantly speed up the process of surveying all the tubes in a furnace. An image will contain temperature readings for multiple tubes as well as background objects that can be used to determine corrections for reflection errors (see Section 4.3). Many thermal imagers have built-in features to enable automatic corrections for reflections based on an emissivity value and background temperature entered by the user. However, these features should be used with care since the methods do not take into account the geometry of the furnace or the position of the target tube within the furnace. This can often result in significant errors. Better accuracy can be obtained by recording radiance temperatures (which is achieved by setting the emissivity value to 1.00) and applying the methods outlined in Section 4.3 and illustrated in Chapter 7.

A particular advantage of thermal imagers is that they create a permanent record of the measurement, which can be analyzed at leisure and reanalyzed at a later date should more information come to hand.

3.5 The Laser Pyrometer

The laser pyrometer is a spectral-band thermometer with the additional feature of a laser reflectometer designed to measure the emissivity of the target [12]. In the emissivity measuring mode, the laser pyrometer shines a laser beam at the target and measures the intensity of the reflected beam. Equation (2.13) ($\varepsilon + \rho = 1$) is then invoked to determine the value of the emissivity from the measured reflectance. The laser beam has a wavelength near the operating wavelength of the thermometer, so the emissivity is determined at the correct wavelength. This emissivity value can be stored in the instrument to be used for subsequent temperature measurements.

A problem in the emissivity measurement occurs when the reflectance of the tube surface is not isotropically diffuse (see Section 2.5.1). In this case the laser pyrometer tends to over-estimate the value of the emissivity [7]. This is because the emissivity is inferred from a measurement of the retro-reflectance, which will generally be lower than if the reflectance were isotropically diffuse, particularly at high angles of incidence (compare the curves in Figure 2.6 with the isotropically diffuse curve). The problem can be compared with trying to determine the volume of a mountain from a single measurement of its height. The under-estimation of reflectance is counteracted somewhat for surfaces exhibiting enhanced retro-reflectance (see Figure 2.5). For rough surfaces with emissivity greater than 0.7 and for near-normal-incidence measurements, the measured emissivity is generally quite good and is within about 0.05 of the true emissivity. At high angles of incidence and for smooth surfaces, the error is generally somewhat greater.

An important property of commercially available laser pyrometers is that they operate over narrow bandwidths, centered on wavelengths that are clear of atomic and molecular absorption lines. This means that, unlike some of the spectral-band thermometers with broader bandwidths, they are not subject to atmospheric absorption and emission errors (see Section 4.4).

Like some thermal imagers, the laser pyrometer has an algorithm designed to automatically correct for reflection errors using the value of emissivity measured by the laser reflectometer and additional radiance temperature measurements of the surroundings. Again, in furnace tube measurements, the algorithm does not take into account the geometry of the furnace or the position of the target tube within the furnace. This correction algorithm can be disabled by setting the emissivity to 1.00. However, the correction algorithm will function perfectly well if the correct value of effective background temperature (see Section 4.3.7) is entered into the instrument separately for each individual tube and the emissivity is set to the true value of the tube emissivity.