Int J Thermophys (2008) 29:395–402
DOI 10.1007/s10765-007-0327-3

A Graphical Method for Calculating Reflection Errors in Radiation Thermometry

D. R. White · P. Saunders

Published online: 18 December 2007

Abstract This article presents a graphical method to calculate reflection corrections for radiation thermometry. The method is based on the observation that the measured radiance of a target is a linear combination of radiances dependent on the emissivity of the target. The method is most easily implemented as a nomogram, enabling thermometer users to estimate reflection corrections immediately when measurements are taken. The nomogram also provides a visual means of explaining the impact of reflection errors on measurements and for explaining the impact of measurement uncertainties on temperature measurements corrected for reflections.

Keywords Emissivity · Nomogram · Radiation thermometry · Reflection correction · Reflection error · Uncertainty

1 Introduction

Reflection errors occur in most practical applications of radiation thermometry. In high-temperature industrial processes, the object of interest is usually heated and therefore surrounded by radiant walls and heaters. The additional thermal radiation reflected by the surface of interest increases the indicated temperature. Depending on the situation, reflection errors may range from a few degrees to several hundred degrees [1,2]. In some industries, such as the petrochemical and steel industries, reflection errors are a well-recognized and long-standing problem [3–6], and it is now increasingly common for thermometer operators to employ measurement strategies that minimize the reflection errors [1,2] or to apply corrections for the reflections.

D. R. White · P. Saunders (✉)
Measurement Standards Laboratory of New Zealand, P.O. Box 31-310, Lower Hutt 5040, New Zealand
e-mail: p.saunders@irl.cri.nz

Although the utility of reflection corrections is now well established, the algorithm is implemented in only a minority of high-temperature radiation thermometers. Furthermore, such thermometers tend to be among the more expensive models offered by manufacturers. Thus, many operators, using hand-held thermometers to make high-temperature measurements, do not have immediate access to an estimate of the true temperature of their plant.

Reflection errors also affect all measurements made near room temperatures. However, unlike high-temperature thermometers, low-temperature thermometers must also compensate for the detector radiance. Most manufacturers of low-temperature thermometers employ a simple correction algorithm that eliminates both effects, but the algorithm implicitly assumes that the thermometer is at the same temperature as the walls (the source of the reflected radiation) [7]. Unfortunately, the algorithm and its limitations are rarely described in the thermometer manual or manufacturers' literature. The lack of information has two negative effects. Firstly, many users are unaware of the problems of reflection errors. Secondly, when the thermometer is not at the same temperature as its surroundings, the simple algorithm fails and reflection corrections must be calculated manually.

This article describes the development of a nomogram (graphical calculating device) for calculating reflection corrections, and instruction on its use. The nomogram is applicable to both high-temperature and low-temperature thermometers, and enables operators to make corrections rapidly without the need for calculators or spreadsheets. It is also a useful tool for describing the impact of measurement uncertainty on temperatures corrected for reflections errors.

The article first provides an overview of the reflection-error problem and the measurement equation used to correct measurements for reflections. The following sections then develop the nomogram, show how it is used to make corrections, and how it may be used to develop an understanding of the propagation of uncertainty for reflection corrections.

2 Reflection Corrections

To simplify the development of the nomogram, we assume that we wish to determine the temperature, T_s, of a small object in a large uniformly radiant enclosure with a wall temperature T_w (see Fig. 1). As the object is small relative to the enclosure, the enclosure behaves like a blackbody cavity, and the radiance temperature of the enclosure is equal to T_w. A radiometer viewing the object measures and integrates the spectral radiance of the object over a well-defined waveband to give a temperature-dependent measured signal,

$$S(T_s, T_w, \varepsilon) = \int_0^\infty \varepsilon(\lambda) R(\lambda) L_b(\lambda, T_s) d\lambda + \int_0^\infty [1 - \varepsilon(\lambda)] R(\lambda) L_b(\lambda, T_w) d\lambda, \quad (1)$$

where $L_b(\lambda, T)$ is the spectral radiance of a blackbody at temperature T and wavelength λ, according to Planck's blackbody radiation law, $R(\lambda)$ is the spectral responsivity of the thermometer, and $\varepsilon(\lambda)$ is the spectral emissivity of the object of interest.

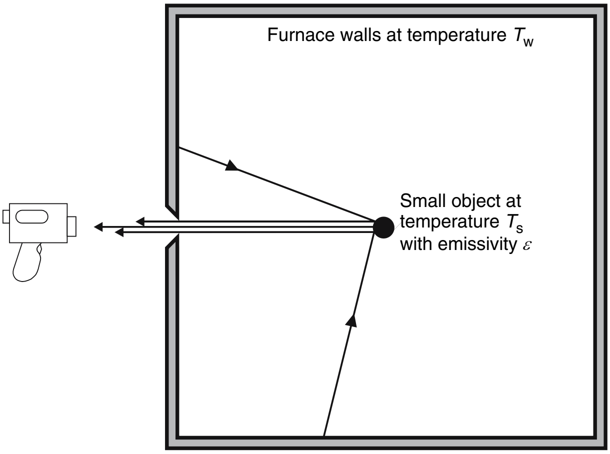

Fig. 1 Simple pictorial representation of how reflection errors occur

The thermometer, which indicates temperature rather than radiance, will usually be calibrated in terms of blackbody temperature, T:

$$S_b(T) = \int_0^\infty R(\lambda) L_b(\lambda, T) \mathrm{d}\lambda. \tag{2}$$

For an object whose spectral emissivity is constant over the passband of the thermometer, Eq. 1 can be simplified to

$$S(T_s, T_w, \varepsilon) = \varepsilon S_b(T_s) + (1 - \varepsilon) S_b(T_w), \tag{3}$$

and this is the measurement equation commonly used to correct for reflection errors [1]. Specifying the measured signal, $S(T_s, T_w, \varepsilon)$, in terms of a radiance temperature, T_m, gives

$$S_b(T_m) = \varepsilon S_b(T_s) + (1 - \varepsilon) S_b(T_w). \tag{4}$$

This equation is the basis of the nomogram. Note that whereas T_m and T_w are directly measured radiance temperatures, T_s refers to the true target temperature, to be determined.

We will also consider the effects of uncertainties or errors in measurements corrected for reflections. The propagation of uncertainties and errors is usually understood in terms of so-called sensitivity coefficients [8], which are derived by differentiating the measurement equation with respect to all measured variables. For Eq. 4, the propagation-of-error equation is

$$\mathrm{d}S_b(T_s) = \frac{1}{\varepsilon}\mathrm{d}S_b(T_m) - \frac{1-\varepsilon}{\varepsilon}\mathrm{d}S_b(T_w) + \frac{S_b(T_w) - S_b(T_m)}{\varepsilon^2}\mathrm{d}\varepsilon. \tag{5}$$

The coefficients of the differentials, $dS_b(T_m)$, $dS_b(T_w)$, and $d\varepsilon$ identify the sensitivity coefficients.

3 The Nomogram

3.1 Application to Reflection Corrections

The nomogram is based on the formula for a linear interpolation between two points $(0, y_1)$ and $(1, y_2)$:

$$y(x) = y_1(1 - x) + y_2 x. \tag{6}$$

This equation has the same functional form as the measurement equation, Eq. 4, and if we make the replacements $x = \varepsilon$, $y(x) = S_b(T_m)$, $y_1 = S_b(T_w)$, and $y_2 = S_b(T_s)$, the equations are the same. This means that a straight-line interpolation on a graph will relate all three temperatures, T_m, T_s, and T_w, so long as the scale of the vertical axis of the graph is marked in direct proportion to the radiometric response, $S_b(T)$, of the thermometer.

Figure 2 shows an example nomogram for a spectral-band thermometer operating at a wavelength of 1 μm. Note particularly the nonlinear vertical axes, and note again that both the measured background (T_w) and measured target (T_m) temperatures are radiance temperatures (made with the emissivity setting on the thermometer set to 1.00), whereas the target temperature (T_s) represents its true value, to be determined by extrapolation. For longer-wavelength thermometers, the vertical scale is more linear.

In a typical application, the thermometer operator carries out five simple steps:

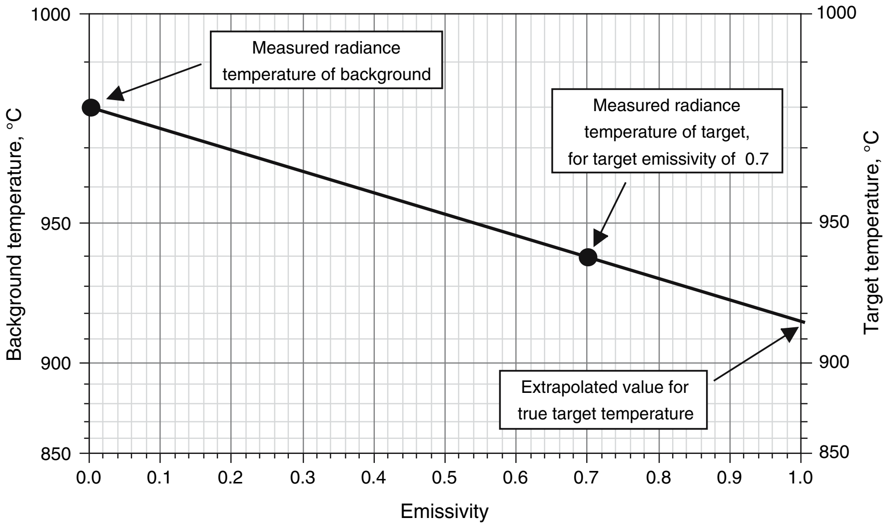

Fig. 2 An example of the nomogram for a spectral-band thermometer operating at 1 μm

1. Adjust the emissivity setting on the thermometer to 1.00 in order to measure radiance temperatures.
2. Estimate the emissivity of the target ($\varepsilon = 0.7$ for the example of Fig. 2).
3. Measure the radiance temperature of the walls and plot the result on the left-hand edge (at $\varepsilon = 0.0$) of the nomogram ($T_\mathrm{w} = 980\,°\mathrm{C}$ for the example of Fig. 2).
4. Measure the radiance temperature of the target and plot the result on the nomogram on the vertical line corresponding to the target emissivity ($T_\mathrm{s} = 940\,°\mathrm{C}$ for the example of Fig. 2).
5. Draw a line on the graph through the two points, and extrapolate to $\varepsilon = 1.0$ to determine the true temperature of the target (T_s is a little less than 920 °C for the example of Fig. 2; the actual value calculated manually is 918 °C).

This procedure applies to both high-temperature thermometers and low-temperature thermometers, but does require the emissivity setting on the instrument to be 1.00. This precludes the use of some fixed-emissivity instruments.

3.2 Application to Uncertainty Propagation

In addition to direct calculation of the target temperature, the nomogram conveys graphically the significance of uncertainties in the different measurements.

Figure 3 shows the influence of the uncertainty in the background radiance temperature on the estimate of the target temperature. One can visualize the lines on the graph as levers with the fulcrum at the target radiance temperature. Hence, an increased wall radiance temperature lowers the estimate of target temperature; this shows that the sensitivity coefficient for the wall radiance is negative. We can also see that the uncertainty in target temperature is amplified by the ratio of the two lever arms. In summary, the uncertainty in background radiance propagates with the sensitivity coefficient,

$$\frac{\partial S_\mathrm{b}(T_\mathrm{s})}{\partial S_\mathrm{b}(T_\mathrm{w})} = -\frac{1-\varepsilon}{\varepsilon}, \tag{7}$$

and this is one of the terms determined earlier in the propagation-of-error equation, Eq. 5.

Figure 4 shows the propagated uncertainty in the measured target radiance temperature. Again, we can visualize the lines as levers, this time with the fulcrum at the wall radiance temperature. In this case, increased target radiance results in an increased true target temperature, so the sensitivity coefficient must be positive. Also, the uncertainty is amplified by the ratio of the positions on the lever arm and is equal to $1/\varepsilon$. Hence, the sensitivity coefficient is

$$\frac{\partial S_\mathrm{b}(T_\mathrm{s})}{\partial S_\mathrm{b}(T_\mathrm{m})} = \frac{1}{\varepsilon}, \tag{8}$$

in accordance with that deduced from Eq. 5.

Figure 5 shows the propagated uncertainty for the uncertainty in the estimate of the emissivity. This example is slightly more complicated than the two above, but the

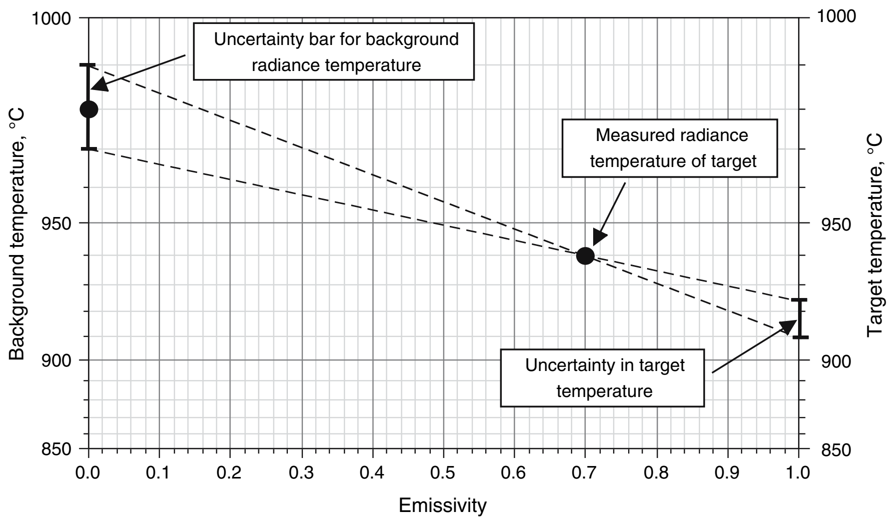

Fig. 3 Propagation of uncertainty for background radiance temperature

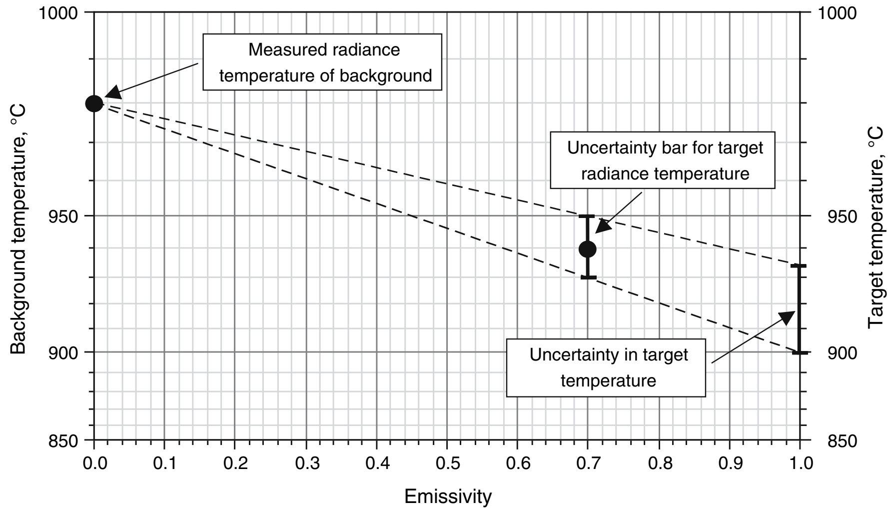

Fig. 4 Propagation of uncertainty for target radiance temperature

lever model can be applied here too. First, we must translate the horizontal movement (due to the uncertainty in the emissivity) to a vertical movement using the slope on the lever, $(S_b(T_w) - S_b(T_m))/\varepsilon$. This situation is identical to that in Fig. 4, so the effect is further scaled by the factor $1/\varepsilon$. Hence, the sensitivity coefficient for the uncertainty in the emissivity is

$$\frac{\partial S_b(T_s)}{\partial \varepsilon} = \frac{S_b(T_w) - S_b(T_m)}{\varepsilon^2}, \tag{9}$$

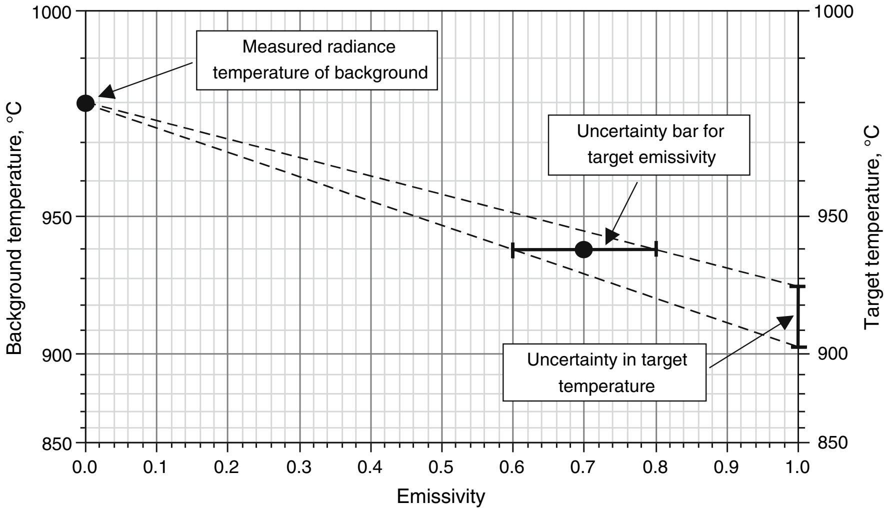

Fig. 5 Propagation of uncertainty for target emissivity

again in accordance with that deduced from Eq. 5.

The most interesting instance of this case is when the measured background and target radiances are the same and the nomogram line is horizontal, so that the uncertainty in the emissivity has no effect on the estimated target temperature. This observation can also be drawn from Eq. 4 by substituting $T_\mathrm{w} = T_\mathrm{m}$, in which case the equation gives $T_\mathrm{s} = T_\mathrm{m}$, independent of emissivity. This corresponds to viewing a blackbody cavity, a situation that is commonly well approximated in the center of reformer furnaces with multiple rows of tubes, where the surroundings are at a similar temperature to the target tube. Blackbody conditions also prevail, for example, in steel preheat furnaces and in pottery kilns.

While this emissivity independence occurs strictly at blackbody conditions, it is clear from the nomogram of Fig. 5 that the closer T_w is to T_m, the less the uncertainty in the emissivity contributes to the total uncertainty in the true target temperature, T_s, in accordance with Eq. 9.

4 Conclusions

This article presents a graphical method to calculate reflection corrections for radiation thermometry. The method is based on the observation that the measured radiance of a target is a linear combination of radiances dependent on the emissivity of the target, and is most easily implemented as a nomogram. The nomogram also provides a visual means for explaining the impact of reflection errors on measurements and for explaining the impact of measurement uncertainties on temperature measurements corrected for reflections. Example nomograms are given showing reflection correction and uncertainty propagation for measured wall radiance temperature, target radiance temperature, and target emissivity.

References

1. P. Saunders, *Radiation Thermometry: Fundamentals and Applications in the Petrochemical Industry* (SPIE Press, Bellingham, Washington, 2007)
2. P. Saunders, D.R. White, Metrologia **32**, 1 (1995)
3. R. Nicholson, J. Inst. Fuel **June**, 258 (1973)
4. S.D. Grandfield, Oil Gas J. **May**, 68 (1978)
5. D.P. DeWitt, Opt. Eng. **25**, 596 (1986)
6. J. Dixon, J. Phys. E: Sci. Instrum. **21**, 425 (1988)
7. P. Saunders, in *Proceedings of TEMPMEKO 2001, 8th International Symposium on Temperature and Thermal Measurements in Industry and Science*, ed. by B. Fellmuth, J. Seidel, G. Scholz (VDE Verlag, Berlin, 2002), pp. 149–154
8. *ISO Guide to the Expression of Uncertainty in Measurement* (International Organization for Standardization, Genève, Switzerland 1995)