Metrological Errors in Non-contact Temperature Measurement Applications

by Albert Book

Practitioners of metrology are often skeptical of non-contact temperature measurement methods, also known as pyrometry. The technical data provided by pyrometer manufacturers, however, document that these instruments do indeed provide very accurate and precise temperature readings. Aside from the importance of selecting an instrument best suited to the particular application, it is crucial to allow for material specific properties and ambient influences in order to obtain a reliable result.

Measuring errors can be avoided if pyrometers are used in a skilled manner. This article exposes the most common sources of error and explains how to minimize or prevent them.

Emissivity

Pyrometers measure the thermal radiation which an object emits. The amount of infrared energy which is radiated will depend on the material properties and surface characteristics of the object. This ability to radiate thermal energy is referred to as "emissivity" (ε). For precise temperature measurement, the pyrometer must be adjusted for the measurand's specific emissivity. Selecting an incorrect emissivity setting can result in considerable errors. The table (**Fig. 1**)demonstrates the temperature deviations (ΔT) when a pyrometer is incorrectly adjusted for 80% emissivity rather than the true 90% emissivity. This error increases when measuring at longer wavelengths or at higher temperatures. Therefore one should always chose a pyrometer which operates at the shortest possible wavelength but is still feasible for the temperature range of the application.

	Object temperature T_{Object}		
	500 °C	800 °C	1500 °C
Wavelength [µm]	ΔT [°C]	ΔT [°C]	ΔT [°C]
λ = 0.78 - 1.06 µ	5	9	25
λ = 1.10 - 1.70 µ	8	14	37
λ = 4.46 - 4.82 µ	23	43	103
λ = 8.0 - 14.0 µ	43	73	150

Fig. 1 *Measurement errors depending on wavelength and temperature at a 10% deviation in emissivity ($\varepsilon_{Instrument}$ = 0.8 and ε_{real} = 0.9)*

Especially in the case of metallic surfaces whose emissivities are either extremely variable or uncertain, measuring at shorter wavelengths will greatly minimize the potential for error. The emissivities of metals tend to increase at shorter wavelengths, and at the same time, the likelihood of error – in the event the emissivity was misadjusted – will tend to decrease.

Transmission loss

In ideal conditions, the atmosphere between the pyrometer and the target will be unobstructed. If gases or particles such as dust, vapour, smoke, or other media such as protective lenses or opaque materials are in the sensor's sighting path, a portion of the energy emitted from the target will be reflected or absorbed and thus affect the measured temperature.

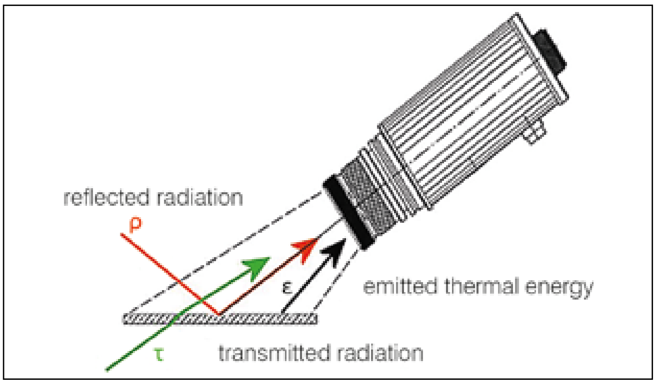

Fig. 2 *Composition of radiation received by the pyrometer's sensor.*

If the transmissivity is known, i.e. such as that of a protective window (τ=0.95), the user can compensate for this by adjusting the pyrometer's emissivity setting.

$$\varepsilon_{pyrometer} = \varepsilon_{object} \cdot \tau_{sighting\ path}$$

$\varepsilon_{pyrometer}$ = Emissivity setting at the instrument
ε_{object} = Emissivity of target object
$\tau_{sighting\ path}$ = Transmissivity of media in the sighting path

Contaminants such dust, oil, or vaporized materials, which may accumulate over a period of time on the pyrometer lens or protective window, pose a greater problem for the measuring task. As the amount of sediment on the lens increases, the pyrometer will produce a lower temperature reading. In such cases, it will be imperative to clean the lens frequently in order to achieve an accurate measurement. The use of an air purge accessory, which circulates air past the optical window, will extend the operational time between lens cleaning. Nowadays there are pyrometers on the market which feature an integrated contamination detection function. When the instrument's optical system is soiled, an alarm will be triggered.

Background and incident radiation

The displayed temperature reading will depend on the total amount of infrared energy detected by the pyrometer's sensor (Φ_Σ). As the equation below shows, the total incident radiation is the sum of the thermal energy emitted from the target plus extraneous radiation, which consists of background radiation reflected from the target, and any radiation transmitted through the target.

$$\Phi_\Sigma = \Phi_\varepsilon + \Phi_\tau + \Phi_\rho$$

ε = emitted from target surface
τ = transmitted through target object
ρ = reflected from target surface

The potential for error due to background radiation will be proportionately lower at a higher target emissivity and when the temperature of the target is considerably hotter than the ambient temperature. Unwanted reflections and background radiation present a considerable problem for applications such as measurement at the outlet of a continuous annealing furnace. The potential for error can be minimized with correct pyrometer alignment, i.e. selecting a target spot which is inaccessible to the thermal radiation from the furnace walls. Radiators such as light bulbs, radiant heaters or lasers often generate great amounts of infrared radiation, a fact which is underestimated in temperature measurement applications.

Especially for laser applications there are devices with blocking filters available, that prevent the influence of the high-energy laser radiation opposite to the very little infrared radiation.

Nothing beats good optics

The occurrence of optical aberrations, stray light, reflections on either optical components or the enclosure, or the diffraction of light waves will cause the sensor to detect radiation which is beyond its intended field of view. The optical system will receive unwanted radiation, referred to as „Size of Source Effect". A pyrometer manufacturer can minimize this potential for error by carefully correcting the optical imaging system, employing antireflection-coated optical components and avoiding stray light and reflections in the instrument. The use of high-grade lenses greatly reduces such sources of error. The „Size of Source Effect" is smallest when the pyrometer is accurately focused at the proper distance. Thus, this effect can be significantly reduced by using pyrometers with focusable optics, if the measuring distance is adjusted correctly.

Caused by physical conditions, the optical error increases with the wavelength. Therefore, an even greater effort is required to correct the optical error for long-wave measuring devices and thus devices for low measuring ranges. The negative impact is, that the displayed measured value of cheap pyrometers, which allow measurements from room temperature, is highly dependent on the selected measuring distance.

The „Size of Source Effect" is negligible when the measured object is considerably larger than the target spot and the surface is almost at the same temperature level. The error can be significantly reduced by using a pyrometer with focusable optics and through proper on-site instrument alignment. An integrated spotlight, a through-the-lens sighting or an integrated video camera make correct alignment and target focusing easy.

Two-Colour Pyrometers

A two-colour pyrometer interprets the ratio of radiant flux emitted by a source at two different spectral ranges. Simplied, the temperature measured can be expressed with the following formula, with λ1 and λ2 representing the two central wavelengths:

$$\frac{1}{T_M} = \frac{1}{T_W} + \frac{\lambda_1 \cdot \lambda_2}{C_2 \cdot (\lambda_1 - \lambda_2)} \cdot \ln\left\{\frac{\varepsilon_1}{\varepsilon_2}\right\}$$

T_M = temperature measured
T_W = true temperature
C_2 = radiation constant

If the emissivities ε1 and ε2 are equivalent, then the true temperature of the target will be equivalent to the measured temperature. As long as ε1 and ε2 are the same, the two-colour pyrometer measures the temperature irrespective of the surface emissivity. In theory, two-colour pyrometers are recommended when the emissivity of the target object is subject to fluctuations. Practice has shown, however, that this is seldomly true, and that the appropriate method of measurement really depends on the application. Because a two-colour pyrometer's temperature reading is based on a ratio, when the emissivities fluctuate and differ at both wavelengths, the measurement error may be even greater than that of a spectral pyrometer. This is especially true when measuring metals and in particular non-ferrous metals since their emissivity fluctuation is particularly dependent on wavelength.

In many cases, however, a transmissivity loss due to dust, vapor, smoke and the like, means an overall lower radiant flux density and results in a loss of signal strength at all wavelengths. In contrast to a spectral pyrometer, a two-colour pyrometer will, in such ambient conditions, still obtain a constant measurement reading.

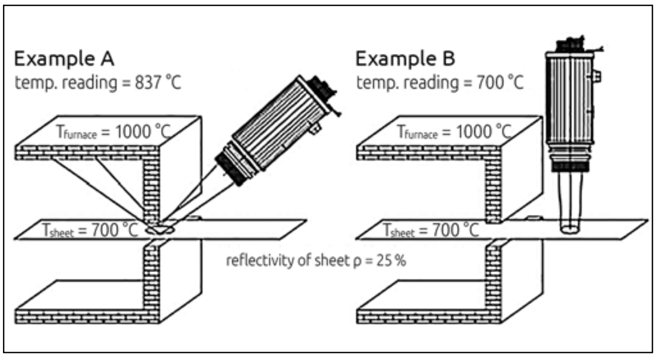

Fig. 3 *Correct pyrometer alignment prevents measurement errors caused by background reflection.*

Innovative two-colour pyrometers enable both temperature measurement at the two spectral wavelengths as well as provide a calculated two-colour temperature reading. With these instruments, the user can decide at the time of installation whether he wants to use the instrument as a spectral or a two-colour pyrometer in order to achieve the most accurate and reproducible temperature readings possible.

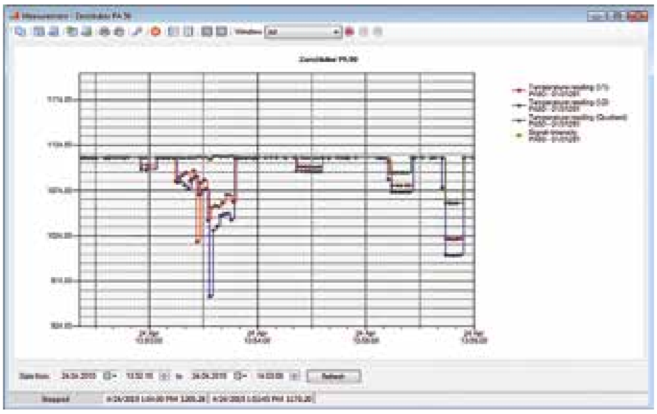

Fig. 4 *Recording of the one-colour and two-colour temperatures with the software CellaView.*

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