radiation thermometry

Part 2— Solving the Emissivity Problem

Here's a look at some recently developed techniques that compensate for unknown variations in emissivity, removing such effects as a source of error in radiation thermometry.

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It is common practice in industrial radiation thermometry either to use the radiance temperature without correction or to apply a correction for a measured or assumed value of emissivity applicable to the problem at hand, Fig. 6. Special filters are available for optical pyrometers to make them "direct-reading" for materials having a spectral emissivity of about 0.4 at 0.65 μm. These are especially convenient in certain steel-mill applications. Most other types of automatic pyrometers discussed in Part 1 provide an adjustment for emissivity to make the instrument direct-reading, assuming that the emissivity is known.

Although useful emissivity data are often difficult to obtain, the heat-transfer problems associated with the exploration of space caused the generation of a large quantity of such data. A special project has been undertaken at the Thermophysical Properties Research Center at Purdue University to critically evaluate and catalog as much of that and other related data as possible. The data thus generated for radiative properties, such as emissivity, have just begun to become available [29, 33–35][2] and should be of considerable aid to those involved in applied radiation thermometry. However, while data from the literature can be a useful guide, they are often little more than that, and from the viewpoint of applied radiation thermometry, the "emissivity problem" remains a very thorny one.

Simulated Blackbodies

The most certain method of avoiding the problem of emissivity effects is to create a cavity in the surface of the target, the shape and dimensions of which can be designed to give an effective emissivity of very nearly unity. This is a nearly ideal solution where the method is applicable; unfortunately, in most instances of industrial interest, it is not, although it is common practice in research and development laboratory applications. Because of their fundamental importance in thermal-radiation physics, the design and effective emissivities of blackbody cavities have received considerable study in the past few years. A substantial body of useful literature is now available, recently reviewed by Bedford [36], in which the effective emissivities of a number of cavity geometries of interest in engineering applications have been well established. Although most studies assume perfectly diffuse interior surfaces, effective emissivities have also been calculated for some cavities having specular surfaces.

Ratio Pyrometers

A second method that has been used extensively with limited success [26, 37–39] is that employed by the "ratio pyrometer." In the ratio pyrometer, the assumption is made that the target has the same emissivity at two wavelengths. The radiance ratio R is then measured at those two wavelengths and is a

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Based on a paper contributed by the ASME Research Committee on Temperature Measurement. This survey was based on work supported by the Pyrometer Instrument Co., Inc., Northvale, N. J.

[2] Numbers in brackets designate References at end of article as well as References at end of Part 1 of the article.

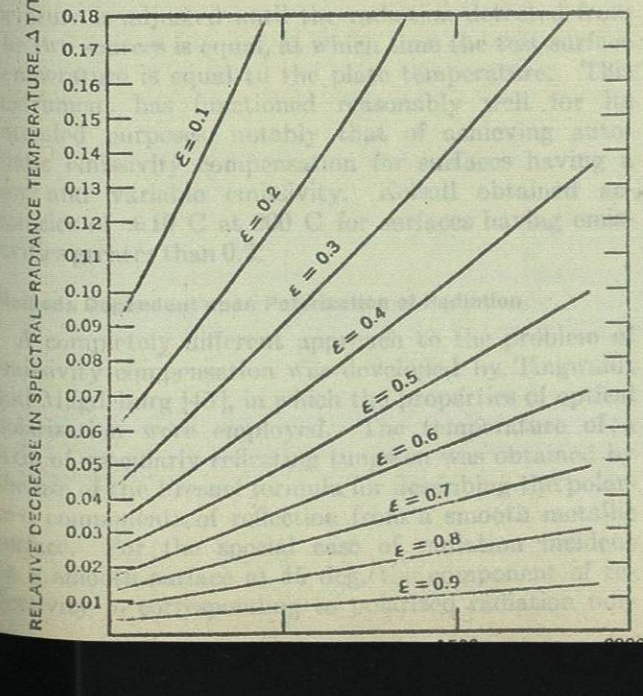
Part 2— Solving the Emissivity Problem

function of the temperature of the target.

$$R = \frac{\epsilon(\lambda_1)}{\epsilon(\lambda_2)}\left(\frac{\lambda_1}{\lambda_2}\right)^{-5} e^{-\frac{C_2}{T}\left(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right)} \qquad (22)$$

If the two emissivities have the same value, $\epsilon(\lambda_1)/\epsilon(\lambda_2)$ cancels out in equation (22) and the ratio is independent of the emissivity. If the emissivity ratio is different from unity (it usually is at least somewhat different), the resulting error tends to be large. If the two spectral bandwidths are not narrow, the effective wavelengths λ_1 and λ_2 are not well defined, and any error in the wavelength ratio is magnified because of its large exponent. The temperature indicated by this kind of pyrometer is called a ratio temperature, and it assumes equal spectral emissivities. If the emissivity ratio is sufficiently reproducible, it may be "calibrated out" of the instrument reading. Ratio pyrometers are inherently less sensitive than monochromatic pyrometers, so their application tends to be at the higher temperatures. In spite of its limitations, the method has found some practical application in the steel industry [39]. Errors in ratio pyrometers have been discussed by Emslie and Blau [37], Pyatt [38], and Ackerman [26].

Fig. 6 Effect of spectral emissivity. Relative amount by which the observed spectral-radiance temperature T_r has been reduced by the effect of spectral emissivity presented as a function of λT_r. Values are based on exact computation from the Planck radiation distribution.



Reflecting Hemispheres

A method developed by Land and Barber [40], and improved by Pattison [41], consists of covering the heated surface with a highly reflecting hemisphere. Multiple reflections within the hemisphere increase the radiance of the surface such that radiation emerging from an aperture in the hemisphere is nearly blackbody radiation. Of all available methods of radiation thermometry other than the use of blackbodies, this method is generally the least influenced by the presence of extraneous radiation. For surfaces having a low thermal conductivity, however, there is a slight change in surface temperature (when the hemisphere is in place) because the hemisphere changes the irradiation on the surface. When applied to a diffuse surface of spectral emissivity ϵ_λ, the effective emissivity of a circular aperture of diameter d in a truncated hemisphere of radius r can be calculated exactly, Fig. 7. Assuming that the hemisphere has an internal spectral specular reflectance ρ_λ, and has its center on the heated surface and its edge a distance S above the surface, the circular aperture viewed along an axis through the center of the hemisphere will have an effective spectral emissivity

$$\epsilon_{\lambda_{\mathrm{eff}}} = \frac{\epsilon_\lambda}{1-(1-\epsilon_\lambda)\rho_\lambda(1-F)} \qquad (23)$$

where

$$F = \left[2\left(\frac{S}{r}\right)^2 + \frac{1}{4}\left(\frac{d}{r}\right)^2\right] \qquad (24)$$

Reflection of Radiation from a Heated Source at Known Temperature

A method that is similar in principle (use of reflected radiance to develop the appropriate blackbody radiance from a specular surface) has been described by Fastie [42] and by Tingwaldt [43]. In this method, the radiation from a blackbody is reflected from the heated specular surface. The sum of the reflected blackbody radiation and that emitted by the specular surface is then measured. When the temperature of the blackbody is adjusted to be equal to that of the specular surface, the radiance of the blackbody is the same as the reflected plus emitted radiance of the specular surface. This method, aside from its inconvenience, suffers somewhat from the requirement for a high degree of specularity. It does not work particularly well for specular surfaces of low emissivity when the radiance of the blackbody is the dominant component measured by the radiation thermometer.

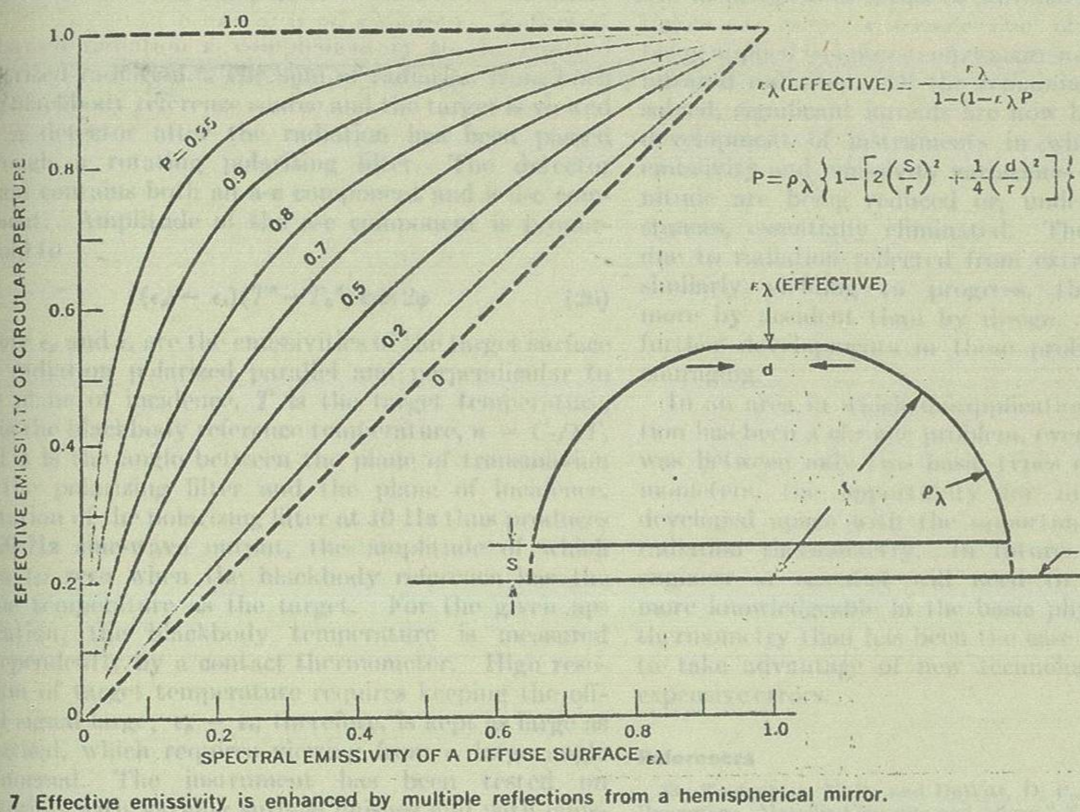


Fig. 7 Effective emissivity is enhanced by multiple reflections from a hemispherical mirror.

High accuracy is needed in the radiance comparison to avoid significant errors under those conditions.

Another method that is similar in principle to those described in the foregoing has been reported by Kelsall [44]. In this method, a heated plate is placed just above the test surface (2 to 5 cm distance), and a radiation thermometer (PbS detector in the case cited) compares the radiation from a region on the upper surface of the reference heater with the radiation from the lower surface of the reference heater after it has been reflected from the test surface. The plate temperature is adjusted until the radiation detected from the two sources is equal, at which time the test-surface temperature is equal to the plate temperature. This instrument has functioned reasonably well for its intended purposes, notably that of achieving automatic emissivity compensation for surfaces having a low and variable emissivity. Kelsall obtained accuracies of ±10 C at 200 C for surfaces having emissivities greater than 0.2.

Methods Dependent upon Polarization of Radiation

A completely different approach to the problem of emissivity compensation was developed by Tingwaldt and Magdeburg [45], in which the properties of optical polarization were employed. The temperature of a strip of specularly reflecting tungsten was obtained by the use of the Fresnel formula for describing the polarized components of reflection from a smooth metallic surface. For the special case of radiation incident on a smooth surface at 45 deg, the component of reflectivity ρ_s corresponding to polarized radiation normal to the plane of incidence and the component ρ_p parallel to the plane of incidence are related by

$$\rho_p = \rho_s^2 \tag{25}$$

Using a narrow-spectral-bandwidth radiation thermometer with a polarizing filter, the ratio of $N_p(\lambda, T)$ to $N_s(\lambda, T)$ was measured, from which a value was calculated for the spectral emissivity. From a direct measurement of the spectral-radiance temperature T_r from the same position and from the relationship $N_b(\lambda, T_r) = \epsilon_\lambda N_b(\lambda, T)$, the temperature T may thus be determined.

It was necessary to exclude extraneous radiation in this measurement, and high accuracy was required in the measurement of radiance. Tingwaldt and Magdeburg obtained values of $\epsilon(\lambda)$ from several measurements in which the deviation among the values was not more than 1 percent, and for which the mean values agreed well with the best available data from other sources, falling between values found by DeVos and Larrabee.

In a more recent development, Murray [46] has applied a variation of the polarization method to materials having diffuse surfaces. While succeeding to a high degree in achieving a radiation thermometer whose readings are independent of the target emissivity, the system, as presently used, requires close proximity to the target. It also shares the characteristic of the Tingwaldt and Magdeburg approach in that it depends on viewing the target from a direction in which the emitted radiation is polarized, but is not restricted to the 45 deg angle. Unpolarized radiation emitted by a [illegible]ly is polarized at least to some extent upon [illegible]ed from the somewhat diffuse target surface. [illegible] component is therefore somewhat [illegible] scattered radiation. Reflected polarized radiation is complementary to the emitted polarized radiation. The sum of radiation from both the blackbody reference source and the target is viewed by a detector after the radiation has been passed through a rotating polarizing filter. The detector signal contains both an a-c component and a d-c component. Amplitude of the a-c component is proportional to

$$(\epsilon_p - \epsilon_s)(T^n - T_b{}^n) \cos 2\phi \tag{26}$$

where ϵ_p and ϵ_s are the emissivities of the target surface for radiation polarized parallel and perpendicular to the plane of incidence, T is the target temperature, T_b is the blackbody reference temperature, $n = C_2/\lambda T$, and ϕ is the angle between the plane of transmission of the polarizing filter and the plane of incidence. Rotation of the polarizing filter at 10 Hz thus produces a 20-Hz sine-wave output, the amplitude of which goes to zero when the blackbody reference has the same temperature as the target. For the given application, the blackbody temperature is measured independently by a contact thermometer. High resolution of target temperature requires keeping the off-null signal large; $\epsilon_p - \epsilon_s$, therefore, is kept as large as practical, which requires viewing from a large angle off-normal. The instrument has been tested on materials with varying surface finishes and with emissivity ranging from 0.05 to 0.47, with a mean error of about ±2 percent of the absolute temperature, over a temperature range from about 150 to 450 C. Geometry-dependent systematic errors of a few degrees are not presently well understood and are under study.

Measurement of Absorptivity Ratio

Another method recently reported for reducing errors due to emissivity effects is a new approach by DeWitt and Kunz [47], who combined radiance temperatures measured with two monochromatic-radiation thermometers operating at different wavelengths with a measured value of the emissivity ratio at those two wavelengths. This is done by irradiating the target with lasers operating first at λ_1 and then λ_2, and measuring in each case a momentary increase in target temperature at a third wavelength. The assumption is then made that the ratio of the increase in target temperature, measured in a third spectral region and corrected for the laser power ratio, is equal to the ratio of the absorptivities at the two wavelengths λ_1 and λ_2, and hence to the ratio of the two emissivities. The method has only been applied to thin-tungsten-strip lamps, where a significant temperature rise could be obtained, and it remains to be determined to what extent the method is applicable to thick pieces of material. A related method involving the measurement of the spectral-reflectance ratio at two wavelengths also shows promise and has been summarized by Bramson [48].

Conclusion

It is apparent that under the influence of changing technology, over the past 10 to 15 years radiation thermometry has undergone a renaissance that is still in progress in terms of automation and achieving higher accuracy; a considerable amount of effort is being applied to lower-temperature measurements using infrared radiation. Of the remaining problems to be solved, significant inroads are now being made in the development of instruments in which the effect of emissivity and emissivity variations of unknown magnitude are being reduced or, under special circumstances, essentially eliminated. The effect of errors due to radiation reflected from extraneous sources is similarly yielding to progress, though apparently more by accident than by design. The outlook for further developments in these problem areas is encouraging.

In an area in which misapplication of instrumentation has been a chronic problem, even when the choice was between only two basic types of radiation thermometers, the opportunity for misapplication has developed apace with the opportunity for improved radiation thermometry. In future applications, the engineer or scientist will need to be substantially more knowledgeable in the basic physics of radiation thermometry than has been the case in the past, both to take advantage of new technology and to avoid expensive errors.

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