

are no satisfactory answers. Major efforts are under way to solve them, and some candidate technologies are now apparent. This does not contradict the common observation that the technology to handle most of our current pollution problems is available and that the limiting factors are manpower, organization, and economic. With the reminder that no new technology will fall from the sky and that performance has to be proved, the development of a new technology to handle our solved pollution problems is a leading avenue to progress.

... in Documenting Product Capabilities

What technical suppliers in the business typically lack is a worthy development budget. It is the disadvantage of present suppliers that new entrants can outpace them with their own technical sophistication. To the degree that a new supplier can develop new technology and document performance and can implement successful application, the profits usually associated with quality products and quality backup may be realized.

... in Matching Customer Needs

As in most industrial-market markets, a profitable route to proprietary advantage is to develop a strong marketing sensitivity to the specific application problems of customer industries. It is in this area of customer service and intelligence that the present suppliers of pollution control products enjoy their market leadership and it is in this area that new entrants can also achieve profitable participation.

... in Acquiring Marketing Competency

An excellent market penetration cannot be assured by a good product alone. Profitable participation in the environmental management business is probably overlooked without informed marketing intelligence. The success of the intelligent toy is in a company's internal knowledge of its own industrial processes, in the hiring of personnel with background in the environmental management business, or in the acquisition of companies with established market ties.

... in Expanding Competitive Intelligence

In addition to the development of a good product and the development of an informed sales staff, another tool for building a successful pollution control venture is a strategic study of competition. After the way content has done his homework on the technical strengths of his intended competition, he can then better make his own thrust in the marketplace by following competition into proven markets which are profitable (and which can stand another supply) by outflanking competitors into new areas of opportunity, by exploiting relative corporate strengths, and by matching competition in areas where head-to-head conflict is inevitable.

... in Being Ready at the Right Time

At the rate that the pollution control movement threatens to accelerate, it has been the concern of many that it is too late to begin an effective drive into this marketplace. A national program has not kept up with national ambition, however, it is not too late. There is still time to take the time to do it right.

Environmental management business lies in their knowledge of the problems of their customers, their personal familiarity with purchasing and engineering staffs, and their ability to adapt a portion of off-the-shelf equipment to a specific situation. Typical weaknesses of these companies lie in their financial resources, their research and development activities, and their capability for developing new technologies needed to control pollution. To meet these competitors, the new entrant must challenge their marketing prowess and at least equal their technical-product systems. To beat them, one must have a superior product and at least equal their marketing capabilities.

Energy versus Enterprise Companies. The new entrants are also advised to keep an competitive eye on other companies that can be expected to enter the business in the future. Thus, what may appear to be a competitive advantage now may become one of its disadvantages as more companies enter the marketplace. Thus, the foregoing description of typical advantages and disadvantages of the new entrant is a transitional one depending upon the inroads made by power and more technically based competitors.

... in Timing

The Legislative Record is Data. In reviewing pollution regulation in this country, one must remember that until 10 years ago the existence of a pollution regulator in corporate decision-making was unknown. Certainly, the governmental machinery necessary to understand, regulate, and enforce pollution control was essentially nonexistent. What has been seen in the development of a completely new governmental system to handle an entirely new social issue in a very short time. If there has been a large amount of industry, regulation, and mistaken management in the effect, it must be understood in this light.

While that is not an excuse for oversight, mistakes, ill-advised laws, and after-the-fact regulation and provisions will continue to be the pollution control business and draws closer to enforcement. There has been a shortage of knowledgeable manpower to administer these laws in the past and there will be so for some time. There has also been a lack of understanding of the nature of pollution, a lack of the ability to pay for the control of it, and a lack of the political sense needed for effective enforcement—conditions that will continue to impede progress in the future.

There are hopeful signs that at least one aspect of the situation is beginning to change. As in any new area of social concern, the earlier years are characterized by exaggerated positions on either side. That conservative-minded projects and industry specialists have dominated much of their resistance. There is a growing awareness of both the need to do something about pollution and the high social cost involved in controlling it. With more intelligent appreciation of these practicalities by both sides, unopposed legislation, more sensitive enforcement, and more responsible pollution control practice is beginning to develop.

Where Might the Profits Be ...

... in Solving Pollution Problems

There are many pollution problems for which there

Radiation Thermometry

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.

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.

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

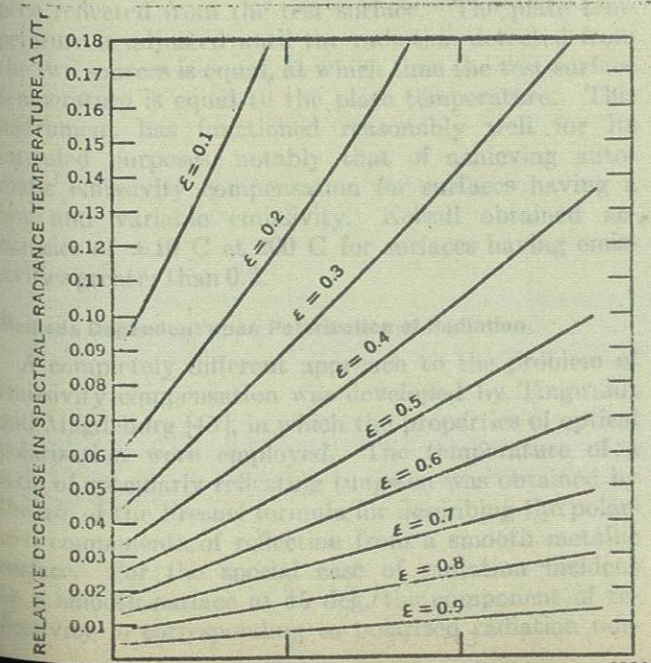
Part 2— Solving the Emissivity Problem

function of the temperature of the target.

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

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,

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.



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].

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

$$\epsilon_{\lambda,eff} = \frac{\epsilon_\lambda}{1 - (1 - \epsilon_\lambda)\rho_\lambda(1 - F)} \quad (23)$$

where

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

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.

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. The "emissivity problem" remains a very lively one.

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 when 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 the radiometric physics, the design and effective emissivity of blackbody cavities have received considerable study in the past few years. A substantial body of useful literature is now available recently reviewed by Bevilacqua [30], in which the effective emissivity 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.

It is common practice in industrial radiation thermometry either to use the radiance temperature with an assumed value of emissivity applicable to the problem at hand, Fig. 6. Special filters are available for many pyrometers to make their "effective" for narrow-band spectral emissivity of about 0.4 at 0.65 microns. These are especially convenient in certain steel and applications. Just other types of emissivity pyrometers discussed in Part I 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 expansion of space toward the generation of a large quantity of such data. A special project has been undertaken at Purdue University to carefully evaluate and catalog as much of this and other related data as possible. The data thus generated for other five properties, such as emissivity, have just begun.

A second method that has been used extensively with limited success [36, 37, 38] 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 is then measured at these two wavelengths and is a

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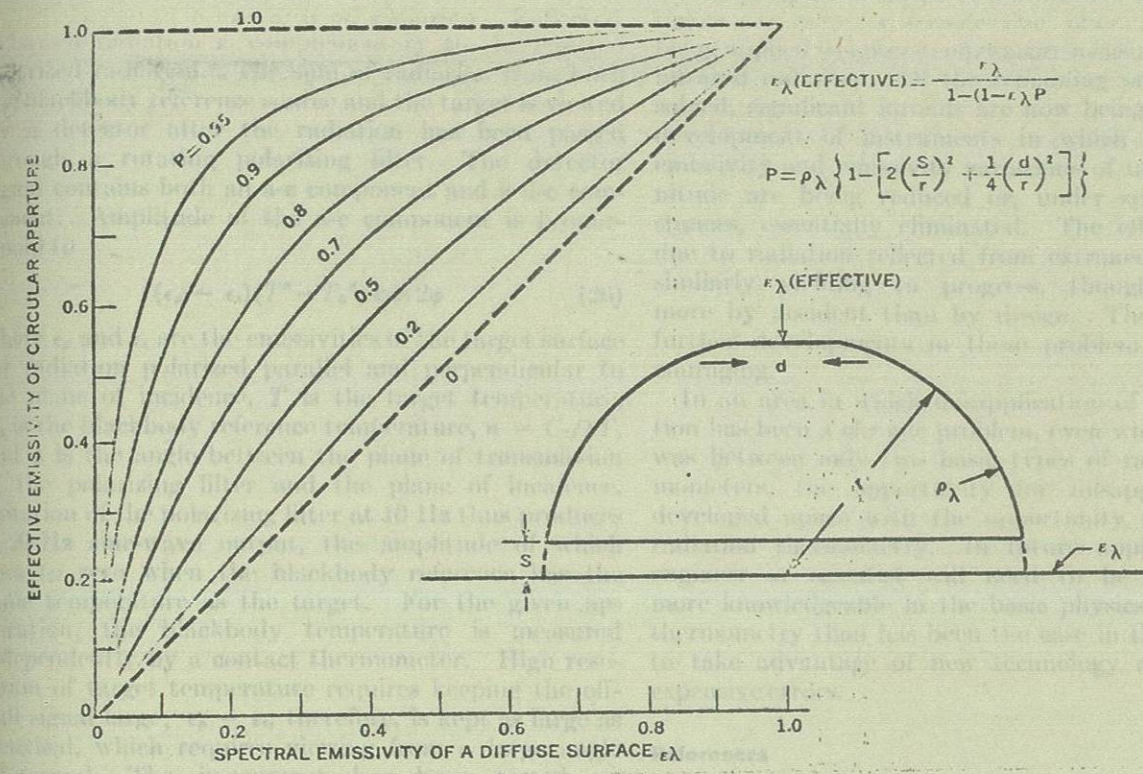


Fig. 7 Effective emissivity is enhanced by multiple reflections from a hemispherical mirror.

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 nor-

mal 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 $N_s(\lambda, T_r) = \epsilon_{\lambda} N_b(\lambda, T)$, 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

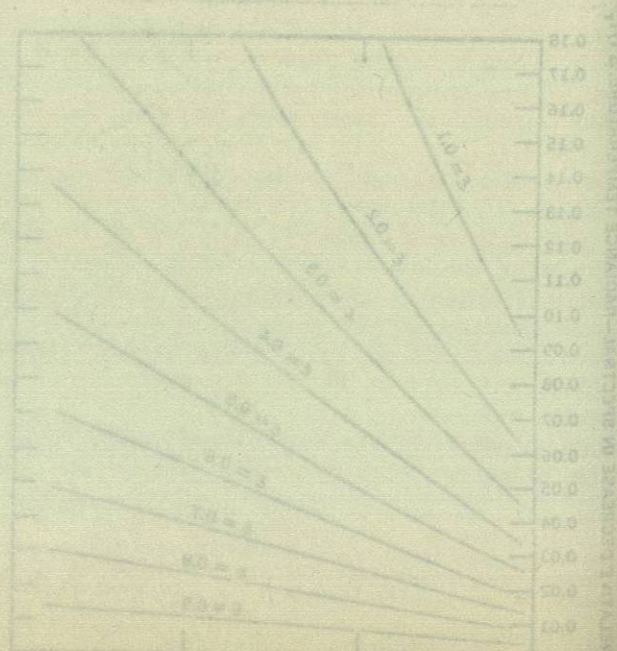
and any error in the wavelength ratio is magnified because of the large exponent. The temperature indicated by this kind of pyrometer is called a ratio temperature, and it assumes equal spectral emissivities. If the emissivity ratio is sufficiently reproducible, it may be "calibrated out" of the instrument reading. Ratio pyrometers are inherently less sensitive than monochromatic pyrometers, so their application tends to be at the higher temperature. In spite of its limitations, the method has found some practical application in the steel industry [30]. Errors in ratio pyrometers have been discussed by Lathin and Lathin [31], Gort [32], and Ackerman [33].

A method developed by Land and Barber [40] and adopted by Johnson [41] consists of covering the heated surface with a highly reflecting hemisphere. Inside the hemisphere, within the hemisphere, the temperature of the surface such that certain contours form an aperture in the hemisphere's nearly black body radiation. Of all available methods of radiation thermometry other than the use of blackbodies, this method is generally the best indicated by the precision of experimental 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 causes the radiation on the surface. When applied to a diffuse surface of spectral emissivity ϵ , the effective emissivity of a circular aperture of diameter d in a hemispherical hemisphere can be calculated exactly, Fig. 7. Assuming that the hemisphere has an internal spectral radiance A_{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

$$\epsilon_{\lambda}(\text{EFFECTIVE}) = \frac{\epsilon_{\lambda}}{1 - (1 - \epsilon_{\lambda})P} \tag{26}$$

$$P = \rho_{\lambda} \left\{ 1 - \left[2 \left(\frac{s}{r} \right)^2 + \frac{1}{4} \left(\frac{d}{r} \right)^2 \right] \right\} \tag{27}$$

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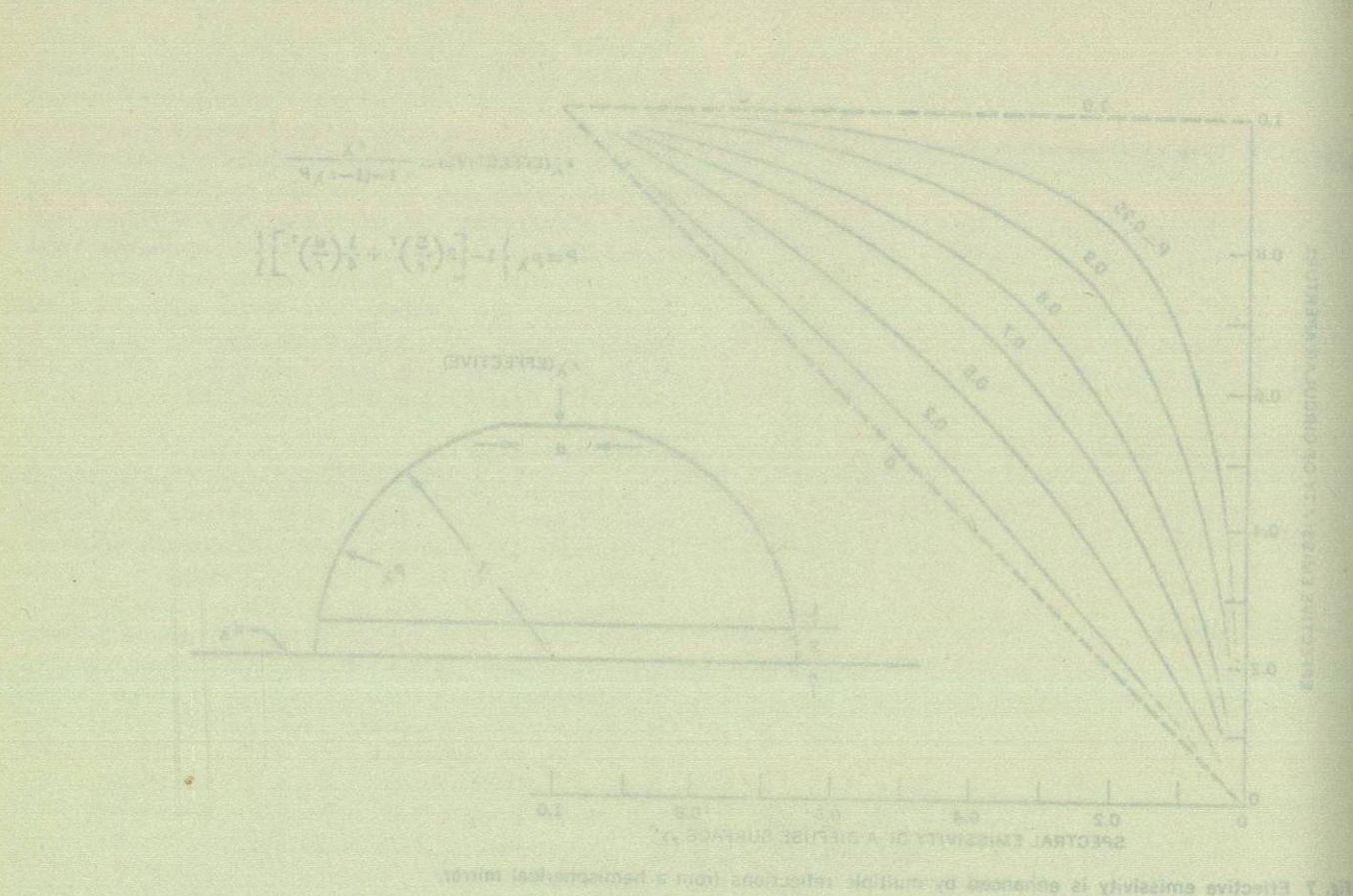


Fig. 7 Effective emissivity is enhanced by multiple reflections from a hemispherical mirror.

high accuracy is needed in the radiation measurement method that is similar in principle to that described in the foregoing has been reported by [44]. In this method, a heated plate is placed just behind the detector (the detector in the foreground) and the radiation from a region on the upper surface of the mirror, heated with the radiation from the lower surface of the heated plate, is reflected back toward the detector. The plate temperature is adjusted with the radiation detector from the two sources is equal to the plate temperature. This treatment has functioned reasonably well for the intended purposes, notably that of reducing the error in emissivity measurement for surfaces having a wide range of emissivity. [44] also obtained an accuracy of $\pm 10\%$ at 200°C for surfaces having emissivities greater than 0.2.

A completely different approach to the problem of emissivity compensation was developed by [45] and [46], in which the proper use of optical polarization was employed. The temperature of a light of spectrally reflecting surfaces 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 reflected radiation is polarized, but is not reflected to a detector corresponding to polarized radiation emitted by a source.

In a more recent development, [47] has applied a variation of the polarization method to surfaces having diffuse surfaces. While according 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 shows the dependence in the target and wavelength approach in that it depends on viewing the target from a direction in which the radiation is polarized, but is not reflected to a detector.

Neighboring 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 were well within the best available data from other sources, taking between values found by [47] and [48].

It was necessary to reduce extraneous radiation in this measurement, and high accuracy was required in the measurement of radiance. The graphs and Neighboring 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 were well within the best available data from other sources, taking between values found by [47] and [48].

radiation is polarized at least to some extent upon reflection from the somewhat diffuse target surface. The polarized component is therefore somewhat different from the unpolarized 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

$$(\epsilon_p - \epsilon_s)(T^n - T_b^n) \cos 2\phi \quad (26)$$

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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