

I. The Fundamentals of Infrared Temperature Measurement

It is about one hundred years since the physical laws and mathematics of infrared heat transfer were established. In 1894, Stefan documented the relationship between the radiation emitted from a **black** surface and its absolute temperature; Boltzman simultaneously derived the relationship from purely theoretical considerations. That relationship being:

$$\underline{E_b} = s T^*(4) \text{ (Btu/ ft}^2 \text{ -hr) or (watts/cm}^2\text{)}$$

Note: $T^*(4)$ is the fourth power of the absolute temperature.

where (E_b) is the energy radiated by the surface of a black body, a perfect emitter, at an absolute temperature (T). The constant (s), is the Stefan-Boltzman constant having a value of $s = 0.173 \times 10^{(-8)}$ in English units and $s = 5.673 \times 10^{(-12)}$ in metric units. It is important to note the fourth power relationship of radiated energy to absolute temperature; **few engineering phenomenons are so temperature dependent and span such an enormous range ie from near absolute zero to 3000F (3460 R) or 1649 C (1921K) which are common temperatures for engineers to handle.**

In 1900, Max Planck described **the distribution** of radiated energy from a surface as a function of the wavelength of the radiated energy; Planck's Law being:

$$\underline{E_{b\lambda}} C_1 \lambda^{-5} \left(e^{C_2/\lambda T} - 1 \right)^{-1}$$

where (c_1) and (c_2) are constants whose values depend on the measurement units and (λ) is the wavelength. The importance of Planck's law to engineers is that it clearly **notes the** extreme dependency of the thermal radiation **process on wavelength**. With the infrared spectrum going from 0.75 microns to 80 microns (750 to 8000nm) we have an enormous dynamic range to cover; fortunately most infrared engineering interest is in the near and mid-infrared range below 20 microns. However, even for a narrow range (1-10 microns) **Planck's law is complicated and when we introduce the notion of emissivity, which may vary with wavelength, only the simple relationships can be integrated to obtain the radiation emitted by a surface at a given temperature.** Planck's Law as written above is for a **black body; one which radiates at 100% efficiency at a given wavelength . . . no such material** exists. Incorporating

emissivity into Planck's equation and covering the wavelength interval of interest gives us the integral form:

$$E_{\Delta\lambda} = \int_{\lambda_s}^{\lambda_L} \varepsilon(\lambda, T) \frac{C_1}{\lambda^5 (e^{\frac{C_2}{\lambda T}} - 1)} d\lambda$$

From the above it is easy to see why we would like to treat emissivity as a constant to get it 'outside' of the integration process. The term "grey" body is applied to materials having a constant, but less than 100% radiating efficiency (e < 1.0) over the waveband of interest. Unfortunately, for most engineering materials emissivity is a function of temperature and may also be a function of geometry (angle off the normal to a surface).

There is one more principle and one more practical factor to keep in mind. The practical aspect is that for most materials the ability of a material to emit radiant energy equals its ability to absorb radiated energy. (This is only true if the temperature difference between emitter and receiver are near equal and assumed true if temperatures are between 0-**3000F.**) Thus (e = a) where (a) is the absorptivity. Finally, there is Kirckoff's relation which accounts for radiant energy being received by a surface; for a unit of radiant energy incident to a surface we have:

$$1 = a + r + t$$

where (a) is the absorbed energy, (r) the reflected energy and (t) the energy transmitted through the material. Each of these properties may be wavelength and temperature dependent surface texture can also play a role. Furthermore, many materials are **anisotropic including graphite**; that is the emissivity is also a function of orientation.

The above is not intended to provide a thorough background in infrared technology, solely a "refresher." There are many excellent texts *including: Theory and Practice of Radiation Pyrometry, Dewitt, D.P. and Nutter, G., Wiley - Interscience, 1988.*

II. Conventional Infrared Pyrometry

Infrared thermometers are based on receiving infrared energy from a target, focusing that energy onto a detector which produces an electric output directly related to the received radiant energy. Thermometers may rely on the radiant energy over the entire infrared spectrum but more commonly a specific bandwidth is selected depending on the intended application (metals, glasses, gases etc.) and the performance characteristics of the detector. These are called spectral Thermometers since they respond in a discrete bandwidth. For common single bandwidth Thermometers there is a dilemma; there is one equation (Planck's law) with two unknowns. The instrument receives the radiance (the energy), but it cannot solve for temperature without having an input value for target emissivity. Typically, a user adjusted knob is provided allowing the user to set in values of emissivity; **but where is the user to find valid emissivity values for the target material and process conditions** which exist? Generally there is no convenient and reliable information source **particularly** for the conditions involved. This is a primary reason for general disappointment with or limited use of single bandwidth infrared thermometers.

One frequently touted solution is use of multiple wavebands within a single instrument, ie: the familiar two-color Thermometer. In this case the radiance is measured at two selected wavebands and the emissivity ratio is either internally fixed at a constant value or the user is obliged to set a "ratio" knob which provides the device with the emissivity ratio information required. Unfortunately one again has the problem of knowing the proper value to set the "ratio" knob. There is also a genuine dilemma in that the physics involved would suggest bandwidths very close to or even overlapping while the mathematics show infinite error if the bandwidths are "totally coincident". Furthermore, if a multicolor Thermometer must view a target through a sight glass or through absorbing/emitting gases, proper compensation must be provided **to account for the differing** interference at the two bandwidths.

It is important to note another classic problem. Thermometers receive all of the infrared radiation within a field of view. Energy from the target **can** be both the emitted energy, upon which we depend, but in addition for any environment where an energy source hotter than the target exists, there will be reflected energy incident to the thermometer. Since ($r > 0.0$) for all materials, this extraneous energy is added to the target energy reaching the thermometer. Therefore, even with a correct emissivity setting if an extraneous source exists there will be an error in the thermometer's reading; the error will be positive ie: **a high reading. (This is true for dual waveband thermometers also; and indeed can be worse if the extraneous source is emitting preferentially more energy in one waveband vs. the other.)**

Without knowing the values of emissivity over the temperature range and waveband(s) being used a single bandwidth thermometer cannot provide meaningful values of temperature even when no sources of extraneous radiant energy exist. For the practicing engineer three sources of information exist. First,

there are extensive tables of emissivity data (as a function of temperature and wavelength) in Thermophysical Properties of Materials, Vols. 7-9 which are available in reprint form from UMI in Ann Arbor, Michigan. Unfortunately, the pristine conditions under which practically all of these emissivity data were obtained do not exist; most engineers do not have polished targets in a vacuum. The second sources of information are various engineering handbooks and heat transfer textbooks. Again conditions must be compared and the wavelength of the reported data must be comparable to that of the instrument being used. Finally, laboratory determination of emissivity using samples of the actual target material and precision thermocouples for comparison with the infrared thermometer readings. While this is costly, it is the only sure way to know what values of emissivity to "set-in" to manually operated **infrared thermometer**.

III. The Emissivity Problem

Engineers commonly need to know the temperature of a material without physically touching the target. Examples may be steel in an annealing furnace in a steel plant, a tube carrying the fluids in a hydrogen furnace in a petrochemical plant, a tungsten wire being drawn for a light bulb or a turbine blade being coated in a vacuum chamber. The problem is always the same; what is the emissivity value? The lower the emissivity the greater influence on temperature even though the fourth root of emissivity is involved. With aluminum having emissivity values sometimes below 0.10 and some ceramics above 0.90 the problem **clearly is not trivial. Obviously a thermometer with an emissivity setting of $e = 0.25$ will display incorrect output temperatures if the true emissivity is $e=0.30$** ; for example the error at 2000F (2460R) is 114 deg F. Note, at $e=0.90$ vs. $E = 0.95$ the error is only 33F at the 2000F level; thus the emissivity level is important.

Emissivity is a material property but unfortunately unlike most physical properties used by engineers it may be highly variable even for one material substance depending on temperature, surface texture and even prior history. As a result there are few correlations between emissivity and other physical properties even for one class or type of material. In a very general way we can say that the emissivity of metals is typically lower than that of metal oxides or ceramics and that for metals emissivity tends to increase with temperature while for ceramics (non-conductors) the reverse is true.

The simplest mathematical case is that of a "grey body", one which has constant emissivity but less than one ($E < 1.0$) over the entire infrared spectrum. (This allows bringing the emissivity variable outside of integral in Planck's equation.) This does not resolve the problem for the user of an infrared thermometer having an emissivity input knob nor a two color thermometer user needing to know the ratio of the ratio of the emissivity at the two wavelengths. The user still has the problem of **knowing the emissivity** at the temperature of the target. For metals

this is crucial for surface oxidation will occur at elevated **temperatures** so the **temperature** measurement time history of the target becomes vital.