EMISSIVITY – THE CRUX OF ACCURATE RADIOMETRIC MEASUREMENT

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Abstract - Infrared (IR) radiometry is a very useful form of temperature measurement. Its advantages over contact thermometry are that it has quick response times and it does not have to come in contact with the area being measured. One of its major drawbacks is that it not as accurate as contact thermometry. One of the major sources of this uncertainty is the emissivity of the surface being measured. This is true for calibration of these devices as well. The best way to calibrate an IR thermometer is by use of a near perfect blackbody. However, a near perfect blackbody is not always a practical option for calibration. Flat plates are needed for calibration of some IR thermometers. Emissivity is not always well behaved. Emissivity can vary with time, meaning that a flat plate's surface coating needs to have a burn in time established. Emissivity can also vary with wavelength and temperature. This paper discusses the sources of error for flat plate emissivity. Knowledge of these sources leads to a more accurate calibration of IR thermometers.

WHAT IS EMISSIVITY

Emissivity is a material's ability to radiate as a perfect blackbody. It is a ratio or percentage of power a perfect blackbody would radiate at a given temperature. Every material radiates energy. The amount of radiated power is dependent on the material's temperature and the material's emissivity.

IR thermometers take advantage of this. They measure the amount of power exiting an object in an infrared band. They calculate temperature based on this measured power and the material's emissivity.

BLACKBODIES

The most ideal calibrator for an IR thermometer is a blackbody. This is because blackbodies have an emissivity near 1.000. Their emissivity is defined mostly by their geometry and not their surface coating.

Perfect Blackbody

A perfect blackbody would have an emissivity of 1.000. This would take place in a system where no light or radiation could escape. In the real world, there is no such thing as a perfect blackbody for IR thermometry. This is because there would be no opening for taking a measurement in such a system. However, the perfect blackbody is a good prototype for modeling thermal radiation.

Planck's Law

The mathematical equation describing the spectral power radiated by a perfect blackbody for a given wavelength is Planck's Law. If Planck's Law is integrated over the entire electro-magnetic spectrum, this gives us the Stefan-Boltzmann Law. This is the familiar T to the 4th law (T^4). The problem with the Stefan-Boltzmann Law is that it is not limited to a specific band. To get such a number, we would need to integrate Planck's Law for the limits of this bandwidth. This integral cannot be solved analytically.

$$L(\lambda, T) = \frac{c_{1L}}{\lambda^5 \left[\exp\left(\frac{c_2}{\lambda T} \right) - 1 \right]}$$

$$M = \sigma T^4 = \pi \int_0^\infty L(\lambda, T) d\lambda$$

Figure 1. Planck's Law and Stefan-Boltzmann Law [1 pp 42-43]

Mathematical Challenges Using Planck's Law

The best way to solve for the energy emitted by a blackbody within a given bandwidth is to numerically integrate Planck's Law within the bandlimits. Another way is to use an approximation for Planck's Law. This must be done with caution as it will introduce uncertainty to any calculation of temperature.

The first of these approximations is Wien's Law. It approximates Planck's Law from a wavelength of 0 to just above the peak wavelength for a given temperature. The peak wavelength is predicted by Wien's Displacement Law. The second approximation is Rayleigh-Jeans Law. It is a good approximation for temperatures that are well below the peak wavelength, but is not accurate for the 8 – 14 µm band unless temperatures are much higher than 500°C.

Using Wien's displacement law, the peak wavelength for 23°C is 9.8µm.

$$L = \frac{c_{1L}}{\lambda^5} \exp\left(\frac{-c_2}{\lambda T} \right)$$

Figure 2. Wien's Law [1 p 48]

$$\lambda_{\max} T = c_3$$

Figure 3. Wien's Displacement Law [1 p 43]

Table 1. Symbols in Radiometric Equations [1 pp 24, 42-43, 48]

Symbol	Name	Value and Units
L	spectral radiance	W m^{-2} μm^{-1} sr^{-1}
M	total exitance	W m^{-2}
λ	wavelength	µm
T	temperature	K
σ	Stefan-Boltzmann Constant	5.67051e-8 W m^{-2} K^{-4}
c_{1L}	First Radiation Constant	1.191044e8 W μm^4 m^{-2} sr^{-1}
c_2	Second Radiation Constant	1.438769e4 µm K
c_3	Third Radiation Constant	2897.7 µm K

When using any of these equations, a single wavelength within the bandwidth can be considered. One would think this should be an average of the band limits. For example, one could use 11μm to approximate a calculation for the 8-14μm band. This can present a problem when most of the energy is skewed towards one end of the spectral band such as the case in the 8-14μm band at 500°C. Error should be evaluated mathematically to determine if the error introduced in the calculation will be less than the desired uncertainty.

Cavities

As stated earlier, there is no such thing as a perfect blackbody for IR thermometry measurement. A good approximation of a perfect blackbody is a cavity. A cavity can be a sphere, cylinder, cone or a combination of these. It must have a well controlled uniform temperature on its surfaces. The total emissivity of a cavity depends on its geometry, but is generally close to 1.000. Cavities will typically have an emissivity of 0.99, 0.999 or 0.9999. In any case, the more 9s present in the cavity emissivity, the closer the cavity acts as a perfect blackbody.

A cavity can be impractical to use for some IR thermometers, especially handheld instruments. This is due to the spot size of these instruments. The spot size is the amount of area the IR thermometer sees when measuring temperature on a surface. It should be noted that this does not necessarily mean that 100% of the signal is inside the manufacturer's spot size specification. This is due to optical scatter. As a rule of thumb, a user should have a diameter at least 2 times the spot size for calibration.

Gray Bodies and IR Calibrators

To get past the problem of spot size, a gray body flat plate calibrator is often used. A gray body is a surface whose emissivity is constant regardless of wavelength. This is the best means of calibrating an IR thermometer when a cavity cannot be used. However, most surfaces do not have a well behaved emissivity response over the entire spectral band.

To calibrate an IR thermometer it is desirable to have a value of emissivity close to 1.00 (usually between 0.90 to 1.00). This is because the effects of background temperature are lessened at higher emissivities.

There are several attributes that make a good flat plate calibrator. Most important is the plate's surface and its emissivity. Knowledge of the emissivity of a flat plate calibrator over the bandwidth of an IR thermometer results in a good calibration. Since a flat plate is made of metal, why not use a bare metal surface. There are 2 reasons for this. First, bare metal has very low emissivity. This emissivity usually is anywhere from 0.02 to 0.50 depending on the metal. Second, most metal oxidizes. This does increase the emissivity, possibly up to 0.80, but it also results in a very large uncertainty due to the time dependant variance in emmisivity of oxides.

To get around these problems with metals, the surface is painted. In the 8 – 14 μm bandwidth special paints are available that have an average emissivity of 0.90 to 0.95.

UNCERTAINTY CAUSED BY EMISSIVITY

Emissivity is a large contributor to uncertainty when using a flat plate calibrator. Care must be taken that the user of these calibrators has good knowledge of the emissivity of the plate. Figure 4 shows the error that can be caused by a change in emissivity. For example, if the emissivity of the surface of the calibrator is 0.93, and it is assumed as being 0.95, this will cause an error of 6.6°C at a surface temperature of 500°C when measuring in the 8 – 14 μm band.

Effect of Wavelength

Many charts can be found that list the emissivity of various materials. These are good guides when looking for emissive properties of materials, but they do not tell the whole story. Most materials' emissivity varies with wavelength. In other words, materials have a spectral emissivity response. An IR thermometer integrates the emissivity within its bandwidth. One study showed that the emissivity in the 8 - 14μm band varied between 0.90 and 0.97 with a dependence on wavelength [2]. Other studies show a similar range of emissivities [3].

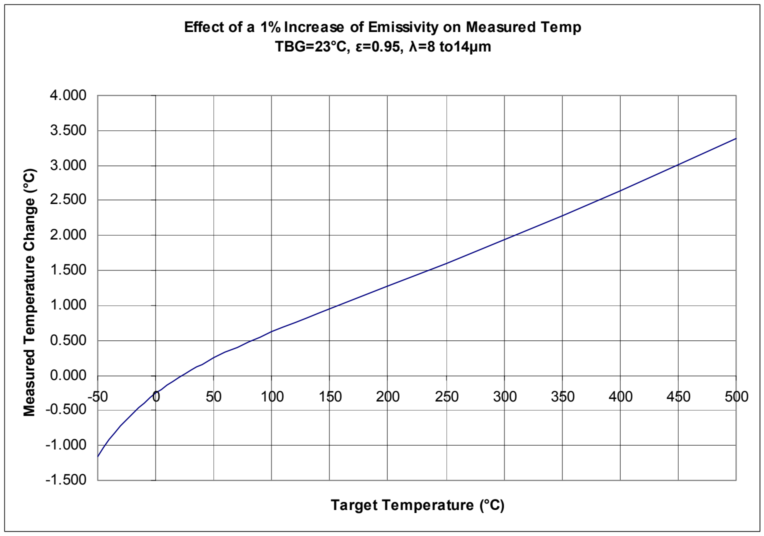

Figure 4. Effect of Emissivity Uncertainty

Effect of Temperature

Emissivity can also vary with temperature. The TRIRAT project was done by a number of laboratories in Europe. It studied traceability in radiation thermometry. The Final Report from the TRIRAT project showed that emissivity could vary widely with temperature [2]. The other effect that temperature can have, is as temperature changes, the amount of energy measure by the IR thermometer shifts within the band. As temperature rises, the energy emitted by the surface shifts from the higher to the lower wavelengths as predicted by the Wien's Displacement Law. This causes the effective emissivity the IR thermometer measures to shift from that of the higher end of the bandwidth to that of the lower end as temperature rises. This is illustrated in Figure 5.

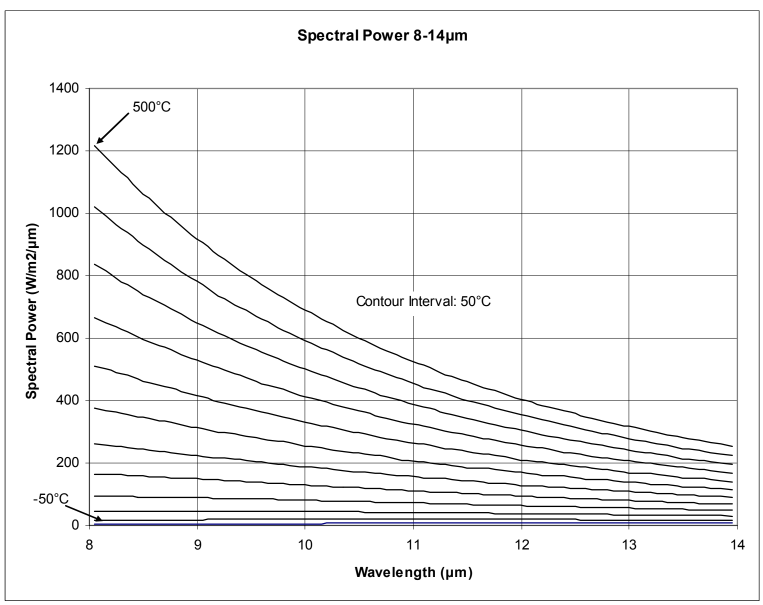

Figure 5. Shift of Energy as Temperature Rises

Effect of Background

The other effect that emissivity has is that of background temperature. If an opaque surface has an emissivity of 0.95, this means that 5% of the energy is reflected as predicted by Kirchoff's Law [1]. This 5% is dependent on the temperature of surfaces that are facing the measured surface. This temperature is called background temperature.

There is a slight uncertainty caused by background temperature. It is not much of a concern when measuring higher temperatures. However, it becomes a concern at lower temperatures. Some of this error is negated if the IR thermometer has background compensation.

A good example to portray the effect of background temperature is a surface at 0°C measured in the 8 – 14 μm band. If the user of the IR thermometer is standing facing the target, the user could very well become the background. This could raise the background from 23°C to 37°C causing a 3.5°C error in the measurement. (We are assuming an emissivity of 0.95 for this example.)

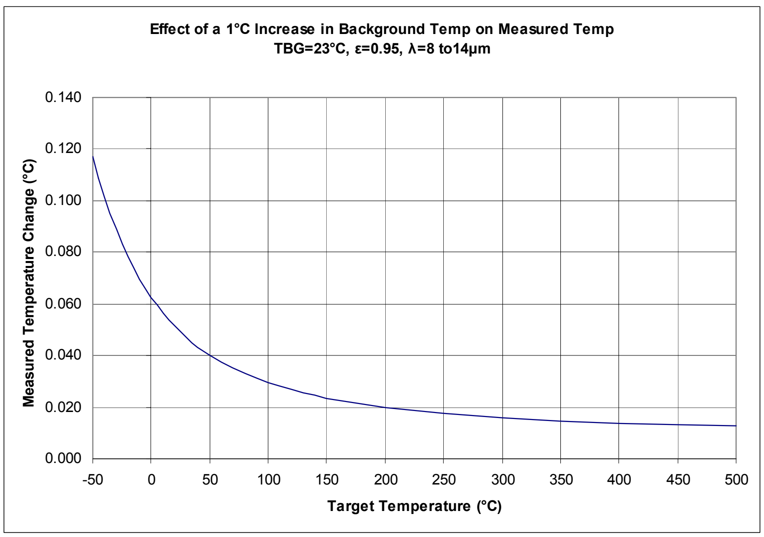

Figure 6. The Effect of Background Temperature

The effects of background temperature get worse as target temperature gets lower. They also get worse as emissivity gets lower. Looking at an extreme example, a perfect reflector would have an emissivty of 0.000. It would be reflecting 100% of the background. In this case, an IR thermometer would measure the temperature of the background, not of the surface.

TAKING CARE OF AN EMISSIVE SURFACE

When using a flat plate calibrator, care must be taken not to damage the emissive surface. Damage can result from a number of sources.

First, care must be taken not to get any foreign material on the surface of the calibrator. Even oil from your skin can damage the calibrator's surface, especially when the surface is heated.

The surface should not be cooled by any method other than natural convection. Forced air can often have oil or water in it. Even water can leave mineral deposits on the surface. Trying to cool the surface too quickly can also cause thermal shock to the emissive surface.

The calibrator should not be left at a high temperature for an extended period of time. This can cause the emissivity of the surface to be degraded.

CONCLUSION

Emissivity is one of the major sources of error in radiometric measurements. Knowledge of the emissivity of the measured surface is of great value to any user of an IR thermometer. As so, great care should be taken to know the effects of emissivity of the surface when measuring it. A thorough knowledge of emissivity and background temperature should be considered when measuring a surface temperature. These factors are even more important when using an IR thermometer calibrator. Paying attention to these factors will provide a better calibration and better IR metrology.

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