Principles of Infrared Thermometry

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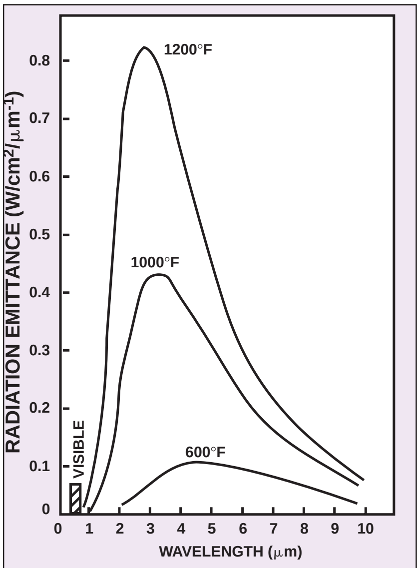
The fundamentals of IR thermometry are an important prerequisite for specifying an accurate monitoring system. Unfortunately, many users do not take the time to understand the basic guidelines, and consequently reject the concept of noncontact temperature measurement as inaccurate.

THEORY AND FUNDAMENTALS

Temperature measurement can be divided into two categories: contact and noncontact. Contact thermocouples, RTDs, and thermometers are the most prevalent in temperature measurement applications. They must contact the target as they measure their own temperature and they are relatively slow responding, but they are inexpensive. Noncontact temperature sensors measure IR energy emitted by the target, have fast response, and are commonly used to measure moving and intermittent targets, targets in a vacuum, and targets that are inaccessible due to hostile environments, geometry limitations, or safety hazards. The cost is relatively high, although in some cases is comparable to contact devices.

Infrared radiation was discovered in 1666 by Sir Isaac Newton, when he separated the electromagnetic energy from sunlight by passing white light through a glass prism that broke up the beam into colors of the rainbow. In 1800, Sir William Herschel took the next step by measuring the relative energy of each color. He also discovered energy beyond the visible. In the early 1900s, Planck, Stefan, Boltzmann, Wien, and Kirchhoff further defined the activity of the electromagnetic spectrum and developed quantitative data and equations to identify IR energy.

This research makes it possible to define IR energy using the basic blackbody emittance curves (See Figure 1). From this plot it can be seen that objects (of a temperature greater than -273°C) emit radiant energy in an amount proportional to the fourth power of their temperature. The concept of blackbody emittance is the foundation for IR thermometry. There is, however, the term “emissivity” that adds a variable to the basic laws of physics. Emissivity is a measure of the ratio of thermal radiation emitted by a graybody (non-blackbody) to that of a blackbody at the same temperature. (A graybody refers to an object that has the same spectral emissivity at every wavelength; a non-graybody is an object whose emissivity changes with wavelength, e.g. aluminum.)



BLACKBODY RADIATION CHARACTERISTICS

STEFAN-BOLTZMANN LAW $Q = \sigma T^4$

WIEN'S DISPLACEMENT LAW $\lambda_M = K/T$

PLANCK'S LAW $Q_\lambda = C\lambda^{-5}(e^{C2/\lambda T}-1)^{-1}$

Figure 1: As shown in curves representing the distribution of energy emitted by blackbodies ranging in temperature from 600°F to 1200°F, the predominant radiation is in the IR region of 0.5-14 µm, well beyond the visible region.

$$E = \frac{L_{GB}}{L_{BB}}$$

The law of conservation of energy states that the coefficient of transmission, reflection, and emission (absorption) of radiation must add up to 1:

$$t_\lambda + r_\lambda + a_\lambda = 1$$

and the emissivity equals absorptivity:

$$E_\lambda = a_\lambda$$

Therefore:

$$E_\lambda = 1 - t_\lambda - r_\lambda$$

This emissivity coefficient fits into Planck’s equation as a variable describing the object surface characteristics relative to wavelength. The majority of targets measured are opaque and the emissivity coefficient can be simplified to:

$$E_\lambda = 1 - r_\lambda$$

Exceptions are materials like glass, plastics, and silicon, but through proper selective spectral filtering it is possible to measure these objects in their opaque IR region.

There is typically a lot of confusion regarding emissivity error, but the user need remember only four things:

- IR sensors are inherently colorblind.
- If the target is visually reflective (like a mirror), beware – you will measure not only the emitted radiation, as desired, but also reflected radiation.
- If you can see through it, you need to select IR filtering (e.g., glass is opaque at 5µm).
- Nine out of ten applications do not require absolute temperature measurement. Repeatability and drift-free operation yield close temperature control.

If the surface is shiny, there is an emissivity adjustment that can be made either manually or automatically to correct for emissivity error. It is a simple fix for most applications. In cases where emissivity varies and creates processing problems, consider dual- or multiwavelength radiometry to eliminate the emissivity problem.

DESIGN ELEMENTS

IR thermometers come in a wide variety of configurations pertaining to optics, electronics, technology, size, and protective enclosures. All, however, have a common chain of IR energy in and an electronic signal out. This basic chain consists of collecting optics, lenses, and/or fiber optics, spectral filtering, and a detector as the front end. Dynamic processing comes in many forms, but can be summarized as amplification, thermal stability, linearization, and signal conditioning. Normal window glass is usable at the short wavelength, quartz for the midrange, and germanium or zinc sulfide for the 8-14 µm range. Fiber optics are available to cover the 0.5-5.0 µm region.

From an applications standpoint, the primary characteristic of the optics is the field of view (FOV), i.e., what is the target size at a prescribed distance? A very common lens system, for example, would be a 1 in. dia. target size at a 15 in. working distance. Using the inverse square law, by doubling the distance (30 in.) the target area theoretically doubles (2 in. dia.). The actual definition of target size (area measured) will vary depending upon the supplier, and it is price dependent. Other optical configurations vary from small spot (0.030 in dia.) for close-up pinpoint measurement, to distant optics (3 in. at 30 ft) for distant aiming. It is important to note that working distance should not affect the accuracy if the FOV is filled by the target. In one technique for measuring FOV, the variable is signal loss vs. diameter. A strict rule is a 1% energy reduction, although some data are presented at half power, or 63.2%

Alignment (aiming) is another optical factor. Many sensors lack that capability; the lens is aligned to the surface and measures surface temperature. This works with sizable targets, e.g., paper web, where pinpoint accuracy is not required. For small targets that use small-spot optics, and for distant optics used in remote monitoring, there are options of visual aiming, aim lights, and laser alignment.

Selective spectral filtering typically uses short-wavelength filters for high-temperature applications (>1000°F, and long-wavelength filters for low temperatures –50°F). This obviously fits the blackbody distribution curves, and there are some technological advantages. For example, high temperature/short wavelength uses a very thermally stable silicon detector, and the short-wavelength design minimizes temperature error due to emissivity variations. Other selective filtering is used for plastic films (3.43 µm and 7.9 µm), glass (5.1 µm), and flame insensitivity (3.8 µm).

A variety of detectors are used to maximize the sensitivity of the sensor. As shown in Figure 2, PbS has the greatest sensitivity, while the thermopile has the least sensitivity. Most detectors are either photovoltaic, putting out a voltage when energized, or photoconductive, changing resistance when excited. These fast-responding, high sensitive detectors have a tradeoff thermal drift that can be overcome in many ways, including temperature compensation (thermistors) circuitry, temperature regulation, auto null circuitry, chopping (AC vs. DC output), and isothermal protection. Drift-free operation is available in varying degrees and is price dependent.

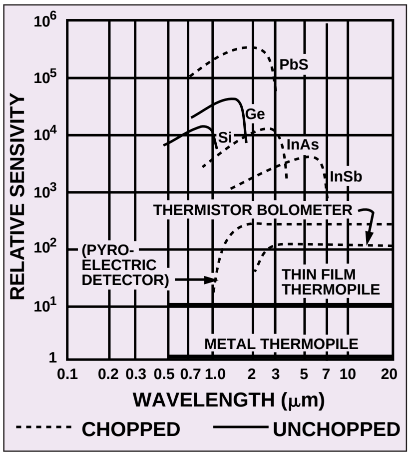


Figure 2: To optimize the respone of IR sensing systems, the detector's spectral response and modulation characteristics must be considered.

In the IR thermometer's electronics package, the detector's nonlinear output signal, on the order of 100-1000 µV, is processed. The signal is amplified 1000 x, regulated, and linearized, and the ultimate output is a linear mV or mA signal. The trend is toward 4-20 mA output to minimize environmental electrical noise interference.

This signal can also be transposed to RS 232 or fed to a PID controller, remote display, or recorder. Additional signal conditioning options involve on/off alarms, adjustable peak hold for intermittent targets, adjustable response time, and/or sample-and-hold circuitry.

On the average, IR thermometers have a response time on the order of 300 ms, although signal outputs on the order of 10 ms can be obtained with silicon detectors. In the real world, many instruments have an adjustable response capability that permits damping of noisy incoming signals and field adjustment on sensitivity. It is not always necessary to have the fastest response available. There are cases involving induction heating and other types of applications, however, where response times on the order of 10-50 ms are required, and they are attainable through IR thermometry.

SINGLE-WAVELENGTH THERMOMETRY

The basic single-wavelength design measures total energy emitted from a surface at a prescribed wavelength. The configurations range from handheld probes with a simple remote meter to sophisticated portables with simultaneous viewing of target and temperature, plus memory and/or printout capabilities. On-line, fixed-mount sensors range from simple small detectors with remote electronics (OEM designs) to rugged devices with remote PID control. Fiber optics, laser aiming, water cooling, CRT display, and scanning systems are among the options for process monitoring and control applications. There are many variations in size, performance, ruggedness, adaptability, and signal conditioning.

Process sensor configuration, IR spectral filtering, temperature range, optics, response time, and target emissivity are important engineering elements that affect performance and which must be given careful consideration during the selection process.

The sensor configuration can be a portable, a simple two-wire transmitter, a sophisticated ruggedized sensing unit, or a scanning device. Visual aiming, laser alignment, non-aiming, fiber optics, water cooling, output signals, and remote displays represent an overview of the various options. These are somewhat subjective, but demand engineering review. In most cases, if it is a simple application, e.g., web temperature, a simple low-cost sensor would do the job; if the application is

Infrared Thermometry Principles Cont'd

complicated, e.g., vacuum chamber or small target, then a more sophisticated sensor is a better choice.

The selection of IR spectral response and temperature range is related to a specific application. Short wavelengths are for high temperature and long wavelengths are for low temperature, to coincide with the blackbody distribution curves. If transparent-type targets are involved, e.g., plastics and glass, then selective narrow-band filtering is required. For example, polyethylene film has a CH absorption band of 3.43 µm, where it becomes opaque. By filtering in this region, the emissivity factor is simplified. Likewise, most glass-type materials become opaque at 4.6 µm and narrow-band filtering at 5.1 µm permits accurate measurement of glass surface temperature. On the other hand, to look through a glass window, a sensor filtered in the 1-4 µm region would allow easy access via viewing ports into vacuum and pressure chambers. Another option, in the case of chambers, is to use a fiber-optic cable with a vacuum or pressure bushing.

Optics and response time are two sensor characteristics that are, in most applications, nonissues, in that the standard FOV of approximately 1 in. at 15 in. is acceptable, and response time of <1 s is adequate. If the application requires a small target or a fast-moving intermittent target, however, then small spot (0.125 in dia.) and very small spot (0.030 in. dia.) may be applicable at a premium. Likewise, distant sighting (10-1000 ft away from the target) will also require an optical adjustment, as the standard FOV will become very large. In some instances, dual-wavelength radiometry is used for these applications, .e.g., wire and distant sighting. The fiber-optic front-end offers engineering flexibility by remoting the electronics from hostile environments, eliminating electrical noise interference and resolving accessibility concerns. It is an intriguing engineering tool that helps solve some unique application problems.

Most sensors have adjustable response in the 0.2-5.0 s range, and typical settings are in the midrange. Fast response can expose application noise, while slow response affects sensitivity. Induction heating requires fast response, while conveyor or web monitoring requires a slower response to reduce application noise. A fast-responding sensor requires a fast-responding controller, SCR power pack, and other regulators. Integrated system dynamics can be defined by the following equation:

$$T = 1.1\sqrt{t_1^2 + t_2^2 \ldots. t_n^2}$$

where:

T = total response

t_1, t_2 = individual elements of the loop

Considering the element of time, there are two types of process dynamics: steady state variations, where there is a fast-moving product that requires close temperature control due to the dynamics of the process, e.g., induction heating of wire. Step changes or ramp response pertains to the very quick heating of a product in a batch process, e.g., rapid thermal annealing of silicon wafers. In these dynamic applications, system responsivity and sensor FOV are critical parameters.

In many cases, target emissivity is not a significant factor. With the proper selection of narrow-band spectral filtering, most materials have a constant emissivity in the 0.90 ±0.05 range. Setting the emissivity at 0.9 µm, the sensor will tend to read within ±5° or 10° of absolute temperature. This application error represents an accuracy variation of about 1% or 2% but, in the real world of IR thermometry, repeatability is critical for control. If, for example, a product is heated to 410°F and the sensor reads 400°F, and you make quality product when the sensor indicates 390-410°F, use the 400 setpoint for control. Most applications do not require NIST calibration standards to produce quality product.

If an application requires accurate, absolute temperature measurement and documentation, the instruments can be calibrated and certified to referenced NIST standards. In addition, there is the need to fully define the application error due to surface emissivity. If a shiny roll must be measured, e.g., the first recommendation is to measure the product passing on the shiny roll. Second, the emissivity adjustment can be made on the sensor using static testing conditions to determine the proper setting. Third, dual-wavelength radiometry may be a viable option.

Single-wavelength IR thermometry represents a very diversified, yet simple, selection technique used in thousands of applications where product temperature control is vital for consistent, high-quality products.

DUAL-WAVELENGTH THERMOMETRY

For more sophisticated applications where absolute accuracy is critical, and where the product is undergoing a physical or chemical change, dual- and multi-wavelength radiometry should be considered. The concept of the ratioing radiometer has been around since the early 1950s, but recent design and hardware changes are yielding higher performance, low-temperature capabilities, and reduced cost.

Dual-wavelength (ratio) thermometry involves measuring the spectral energy at two different wavelengths (spectral bands). The target temperature can be read directly from the instrument if the emissivity has the same value at both wavelengths. This type of instrument can also indicate the correct temperature of a target when the FOV is partially occluded by relatively cold materials such as dust, wire screens, and gray translucent windows in the sight path.

The theory of this design is quite simple and straightforward, and is illustrated by the following equations, where we take Planck's equation for one wavelength and ratio it to the energy at a second wavelength.

$$R = \frac{L_{\lambda 1}}{L_{\lambda 2}} = \frac{\epsilon_{\lambda 1} \cdot C_1 \cdot \lambda_1^{-5} \cdot e^{-C_2/\lambda_1 T}}{\epsilon_{\lambda 2} \cdot C_1 \cdot \lambda_2^{-5} \cdot e^{-C_2/\lambda_2 T}}$$

$$R = \frac{\epsilon_{\lambda 1}}{\epsilon_{\lambda 2}} \cdot \left[\frac{\lambda_1}{\lambda_2}\right]^{-5} \cdot e^{\left[-\frac{C_2}{T}\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)\right]}$$

$$R = \left[\frac{\lambda_1}{\lambda_2}\right]^{-5} \cdot e^{\left[-\frac{C_2}{T_r}\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)\right]}$$

$$\frac{1}{T} = \frac{1}{T_r} + \frac{1n\,(\epsilon_{\lambda_1}/\epsilon_{\lambda_2})}{C_2\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)}$$

If $\epsilon_{\lambda 1} = \epsilon_{\lambda 2}$, then $T = T_r$

where:

R = spectral radiance ratio
T_r = ratio temperature of the surface
ϵ_λ = spectral emissivity

In this process, if the emissivity at both wavelengths is equal (graybody condition), the emissivity factor cancels out of the equation and we find the ratio is directly proportional to temperature.

The same concept can be viewed also in a graphic presentation by taking a small segment of the blackbody distribution curve and measuring some ratios at various emissivities (see Figure 3). Using 0.7 µm and 0.8 µm as the narrow-band filters, the ratio factor remains constant at 1.428 for the range of emissivities down to 0.1.

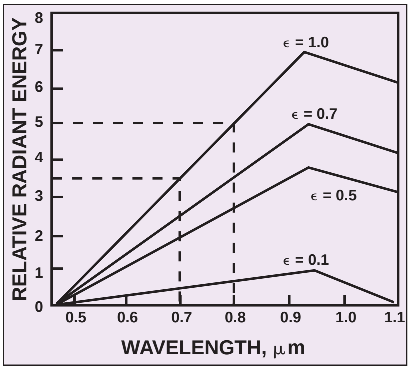


Figure 3: The dual-wavelength system automatically eliminates measurement errors by computing the ratio of the radiant energies emitted by the target in two adjacent wavebands, e.g., 0.7 µm and 0.8 µm.

Similarly, any other changes that are gray in nature will not affect the temperature determined by the dual-wavelength thermometer. These variations include changes in target size such as a wire or a stream of molten glass whose diameters vary during measurement, even in the case of targets smaller than the thermometer's FOV. For instance, suppose that a blackbody target fills only half the thermometer's FOV; instead of a 50% reduction in emittance, this analysis is unchanged. Another example is a case where a target is obscured with smoke or dust, or where an intervening window (e.g., of a vacuum chamber) becomes clouded. As long as the obscured medium is not spectrally selective in its attenuation of radiation, at least in the wavelength region used by the thermometer, the analysis remains the same. The temperature inferred by the dual-wavelength radiometer remains unaffected.

Nonetheless, there are always limits that must be recognized. The dual-wavelength does not perform on non-graybodies, e.g., aluminum; it has difficulty looking through non-gray windows or heated Pyrex; and it tends to measure background temperatures where the background is hotter than the target.

Dual-wavelength thermometers have many applications throughout industry and research as simple, unique sensor that can reduce application error involving graybody surfaces. Figure 4 illustrates examples of total emissivity for a variety of products that have temperature-related varying emissivity. For example, most users would consider graphite to have a high constant emissivity. The fact is, however, that graphite's emissivity varies from 0.4 to 0.65 over the temperature range of ambient to 2000°F. For accurate product temperature measurement and control, dual-wavelength thermometers should be used when these types of graybody materials are being processed at high temperatures.

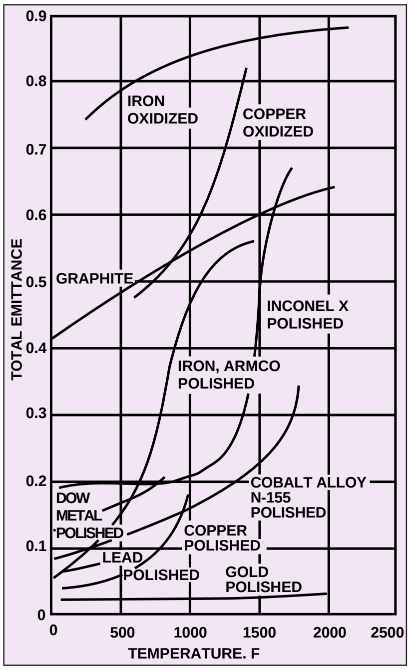


Figure 4: Many materials have emissivity levels that vary with temperature. Several of the most commonly used are compared here.

There are also multi-wavelength thermometers available for non-graybody materials where the emissivity varies with wavelength. In these applications there is a detailed analysis of the product's surface characteristics regarding emissivity vs. wavelength vs. temperature vs. surface chemistry. With these data, algorithms can be generated relating spectral emittance at various wavelengths to temperature.

SUMMARY

A review of the basic application elements is outlined in Figure 5. The surface of a target to be measured is the prime concern. When selecting the instrument, the user must take into account target size, temperature limits, emissivity, and process dynamics as they relate to FOV, spectral response, and response time. It is also essential to characterize the surroundings, e.g., flames, IR heaters, induction coils, and the atmosphere (dust, dirty windows, flames, excessive heat) in order to select the optimum instrument for this application.

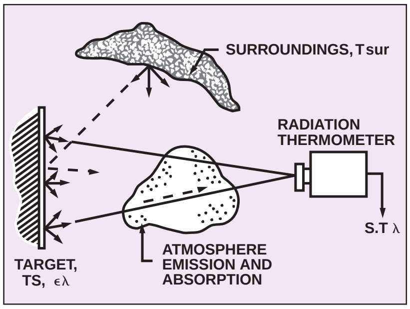


Figure 5: When selecting noncontact temperature measurement instruments, it is necessary to take into account not only the target and its emissivity, but also the surroundings and the invtervening atmosphere.

With regard to performance specifications, calibration accuracy will typically be in the 0.5-0.1% range, while the repeatability of most sensors will be in the 0.25-0.75% range. Pricing on the basic sensor will start at $500 and could go as high as $5000-$6000. In the majority of the applications, price is not an issue; when the sensor is properly installed and used, payback typically is on the order of one or two months.

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