Infrared Thermometry

Understanding and using the Infrared Thermometer

Advances in electronic and detector technology have resulted in a variety of non-contact infrared thermometers (IR) for industrial and scientific use. It is important to understand their major differences in order to select the proper unit for a given application.

Infrared Theory

Energy is emitted by all objects having a temperature greater than absolute zero. This energy increases as the object gets hotter, permitting measurement of temperature by measurement of the emitted energy, particularly the radiation in the infrared portion of the spectrum of emitted radiation. Figure 1 shows a typical infrared radiation thermometer.

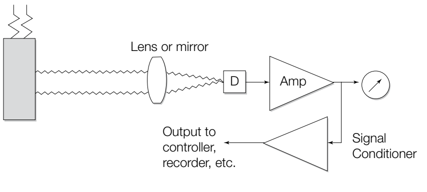

Figure 1: Block diagram, infrared pyrometer

Electromagnetic Spectrum

Infrared radiation is part of the electromagnetic spectrum which includes radio waves, microwaves, visible light, ultraviolet, gamma- and X-rays (Figure 2). These various forms of energy are categorised by frequency or wavelength.* Note that visible light extends from .4 to .7 micron, with ultraviolet (UV) shorter than .4 micron, and infrared longer than .7 micron, extending to several hundred microns. In practice, the .5 to 20 micron band is used for IR temperature measurement.

Planck's Law

The amplitude (intensity) of radiated energy can be plotted as a function of wavelength, based on Planck's law. Figure 3 shows the radiation emission curves for objects at two different temperatures. By convention, longer wavelengths are shown to the right on IR graphs, reverse of electromagnetic spectrum charts, such as Figure 2. The area under each curve represents the total energy radiated at the associated temperature.

Note that two changes occur simultaneously as temperature is increased: (1) the amplitude of the curve increases, increasing the area (energy) beneath it, and (2) the wavelength associated with the peak energy (highest point of the curve) shifts to the shorter wavelength end of the scale.

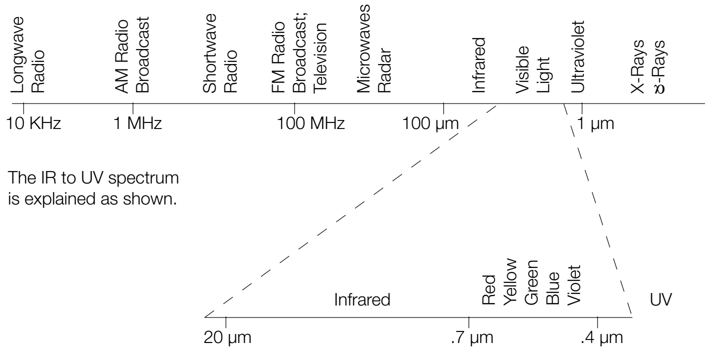

Figure 2: Electromagnetic spectrum and light spectrum

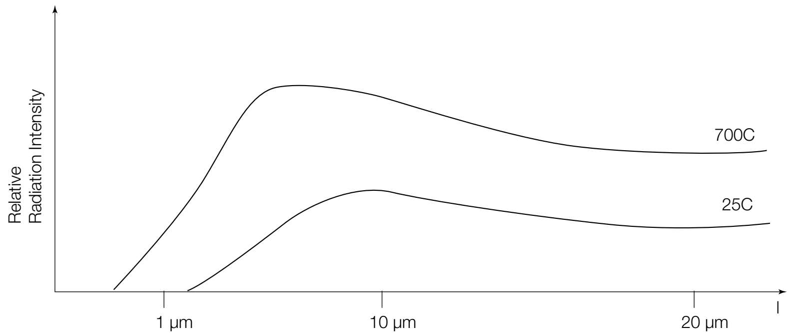

Figure 3: Radiation intensities derived from Planck's Law (Blackbody radiation curves)

This relationship is described by Wien's Displacement Law:

$\lambda_{max} = 2.89 \times 10^3/T$

where λ_{max} = wavelength of peak energy in microns

T = temperature in degrees Kelvin

For example, the wavelength for peak energy emitted from an object at 2617 degrees Celsius (2890 degrees Kelvin) is:

$$\lambda_{max} = 2.89 \times 10^3/2890K = 1.0\ \mu m$$

Another illustration involves heating a steel billet. At about 600°C (1100°F), a dull, red glow is emitted from the steel. As the temperature increases, the colour changes from red to orange and yellow as the peak passes into the visible light spectrum. Finally, the energy emitted throughout the entire visible spectrum is at such a high level that white light is given off by the steel at about 1650°C. Because the peak of the curve shifts as temperature increases, selection of the optimum portion of the spectrum is important to achieving satisfactory infrared thermometer performance.

Emissivity

Emissivity is defined as the ratio of the energy radiated by an object at a given temperature to the energy emitted by a perfect radiator, or blackbody, at the same temperature. The emissivity of a blackbody is 1.0. All values of emissivity fall between 0.0 and 1.0.

Emissivity (E), a major but not uncontrollable factor in IR temperature measurement, cannot be ignored. Related to emissivity are reflectivity (R), a measure of an object's ability to reflect infrared energy, and transmissivity (T), a measure of an object's ability to pass or transmit IR energy. Since all radiation must be either transmitted, reflected or absorbed:

$$A + R + T = 1.0$$

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*Wavelength (λ) is inversely related to frequency (f): $\lambda = c/f$, where c = velocity of the wave; λ is measured in microns (µm); 1 µm = 10^{-6}m.

Consider the example in Figure 4a. Object X is a hot block of material, Y is colder; therefore, heat will be radiated from X to Y. Some heat will be absorbed by Y, some reflected, and some transmitted through Y. The three dispositions must equal 100%, represented as 1.0 for coefficients of absorption, reflection, and transmission. If A = 1.0, all the heat is absorbed; if R = 1.0, then A = T = 0. Usually some combination exists:

A = .7 (70% absorbed)
R = .2 (20% reflected)
T = .1 (10% transmitted)

Sum = 1.0 (100% energy radiated from X to Y)

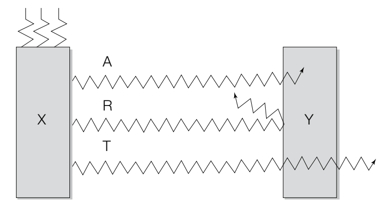

Figure 4a: Energy budget for all radiated IR energy

If an object is in a state of thermal equilibrium, it is getting neither hotter nor colder; the amount of energy it is radiating must equal the amount of energy it is absorbing, so A = E (emissivity). By substitution:

$$E + R + T = 1.0$$

If any two of these values are known, the third is easy to find. Figure 4b illustrates this relationship.

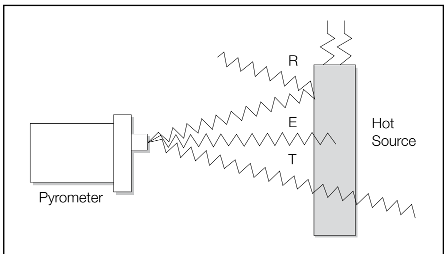

Figure 4b: Total IR radiation reaching pyrometer

Transmission

In some applications, particularly glass and thin-film plastics, transmission becomes an important factor. If it is desired to measure the temperature of these substances using IR, a wavelength must be chosen where the material appears opaque or semi-opaque. Often it is desired to measure temperatures under the surface of an object. This is possible when the material is somewhat transparent at the measured wavelength. Otherwise, selecting a wavelength where the material is opaque minimises measurement errors due to transmitted energy reaching the IR thermometer. If it is desired to make measurements of objects through a glass or quartz window, a short wavelength must be used to take advantage of the ability of the window to pass a high percentage of the IR energy at that wavelength.

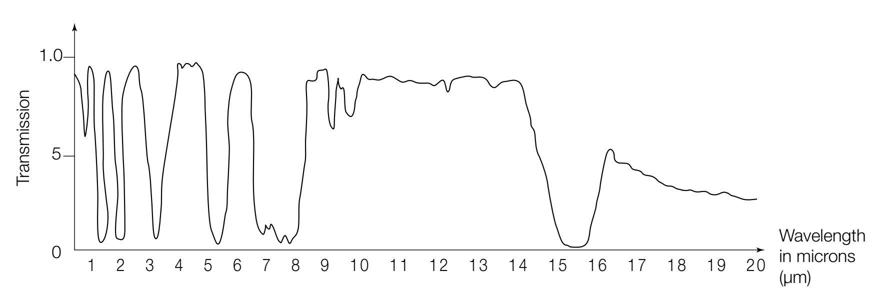

Figure 5: IR transmission through atmosphere

Atmospheric Absorption

One of the first considerations in selecting the spectral response (wavelength range at which an instrument is sensitive to IR) of a device is atmospheric absorption. Certain components of the atmosphere, such as water vapour, CO_2 and other materials, absorb IR at certain wavelengths, increasing the amount of energy absorbed with the distance between the object and the instrument. Therefore, if these absorbents are ignored, an instrument may read correctly when near the object, but several degrees lower a few feet away because the displayed temperature represents an average of the object temperature and the atmosphere temperature. The reading may be affected by changes in humidity or the presence of steam or certain gases. Fortunately, there are “windows” in the IR spectrum which allow these absorption bands to be avoided. Figure 5 illustrates these windows.

Optics

Target size and distance are critical to accuracy for most IR thermometers. Every IR instrument has a field of view (FOV), an angle of vision in which it will average all the temperatures it sees (Figure 6).

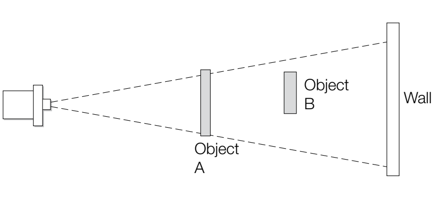

Figure 6: Field of view of instrument

Object A fills the field of view of the sensor; the only temperature seen is that of object A, so the temperature of object A will be accurately indicated. But if object A is removed, object B and the wall share the field of view. The indicated temperature, somewhere between that of object B and the wall, will depend on the relative areas of each filling the circular field of view. If it is desired to measure the temperature of object B, one of four things must be done:

1. Move the thermometer closer to object B, or vice versa.
2. Increase the size of object B until it fills the thermometer’s FOV.
3. Decrease the emissivity compensator (described later) to compensate for the loss of energy.
4. Get a thermometer with a smaller FOV.

Field of view is described either by its angle or by a distance-to-size ratio (D:S). If D:S = 20:1, and if the distance to the object divided by the diameter of the object is exactly 20, then the object exactly fills the instrument’s field of view. A D:S ratio of 60:1 equals a field of view of 1°.

Since most IR thermometers have fixed focus optics, the minimum measurement spot occurs at the specified focal distance. Typically, if an instrument has fixed-focus optics with a 120: 1 D:S ratio and a focal length of 1.5 m the minimum spot (resolution) the instrument can achieve is 1.5 m divided by 120, or 12.5 mm at a distance of 1.5 m from the instrument. This is significant when the size of the object is close to the minimum spot the instrument can measure.

Most general-purpose IR thermometers use a focal distance between 50 cm and 150 cm; special close-focus instruments use a 12.5 mm to 300 mm focal distance, and may be equipped with a light-spot aiming device to ensure that the instrument is measuring the exact spot desired. Some long-range instruments for checking insulators and transformers on pylons use a 15 m focal distance. Sighting scopes are often used at longer distances or for small spot sizes. Some IR thermometers use variable-focus optics, especially high performance fixed-mount types with through-the-lens sighting.

Fibre optics are alternatively used in special applications where there is not enough space to mount a sensing head, or where radio frequency interference (RFI) of high intensity could cause erratic readings.

Emissivity

The ideal surface for IR temperature measurement would have an emissivity of 1.0. Such an object is known as a blackbody, or perfect radiator/absorber. For these objects, R = T = 0. The term “blackbody” is somewhat misleading, in that colour is irrelevant in the IR spectrum because coloured light has much shorter wavelengths. In practice, however, most objects are either graybodies (which have an emissivity of less than 1.0 but the same emissivity at all wavelengths), or non-graybodies (which have emissivities which vary with wavelength and/or temperature). This last type of object can result in serious measurement accuracy problems because most IR thermometers mathematically translate measured IR energy into temperature. As an object with an emissivity of .7 emits only 70% of the available energy, this would cause the indicated temperature to read lower than actual. IR thermometer manufacturers usually address this problem by installing an emissivity compensator, a calibrated gain adjustment which increases the amplification of the detector signal to compensate for the energy lost due to an emissivity less than 1. This same adjustment can be used to correct for transmission losses through viewing ports, smoke, dust, or vapours. For example, setting the compensator to .5 for an object with that emissivity results in a gain increase by a factor of 2. If a viewing port is used to sight the object in a vacuum chamber, and the transmission through the port is 40% (T= .4), the errors are in series, so the net compensator setting is .5 x .4 = .2. The resulting amplification factor of 5 will compensate for all energy losses.

Emissivity Versus Wavelength

For many materials, particularly organics, emissivity does not vary appreciably with wavelength. Other materials, such as glass and thin-film plastics, present severe transmission losses at some wavelengths, particularly the shorter wavelengths. These will be discussed later.

Metals, in almost all cases, tend to be more reflective at long wavelengths, hence their emissivity improves inversely with wavelength. A problem arises with low-temperature metals, where the shortest usable wavelength depends on the point at which insufficient energy exists to produce a detector output. In these cases a compromise is necessary. Further discussion is found in the section on metals applications.

Determination of Emissivity

The emissivity of most organic substances (wood, cloth, plastics, etc.) is approximately 0.95. Metals with smooth, polished surfaces can have emissivities much lower than 1.0. The emissivity of a material can be determined in one of the following ways:

1. Heat a sample of the material to a known temperature as determined by a precise sensor in an oven, and measure the temperature of the object with the IR instrument. Use the emissivity compensator adjustment to force the indicator to display the correct temperature. Use this value of emissivity for measurements of this same material in the future.
2. For relatively low temperature (up to about 250°C or 500°F), a piece of masking tape can be placed on the object and the temperature of the masking tape measured with the IR thermometer using an emissivity setting of 0.95. Next, measure the object temperature, and adjust the emissivity compensator until the display shows the correct temperature. Use this emissivity value for future measurements of this object.
3. For very high temperatures, a hole, the depth of which is at least 6 times the diameter can be drilled into the object. This hole acts as a blackbody with an emissivity of approximately 1.0, and the temperature measured looking into the hole will be the correct object temperature. As in example 2, use the emissivity compensator to determine the correct setting for this object's future measurements.
4. When a portion of the surface of the object can be coated, a dull black paint will have an emissivity of about 1.0. Other non-metallic coatings such as mold release, spray baking powder, deodorant, and other coatings may also be used. Measure the known temperature as before, and use the emissivity adjustment to determine the correct emissivity value.
5. Standardised values of emissivity are available for most materials. For a detailed listing of emissivities, refer to "Thermal Radiative Properties", (volumes 7, 8 and 9) by Y.S Touloukian and D.P. DeWitt, published by IFI/ Plenum Data Corporation, Subsidiary of Plenum Publishing Company, 227 West 17th St, New York, New York 10011.

Spectral Response - Wideband, Narrowband, and Ratio IR Thermometers

One means of categorising IR thermometers is by spectral response: the width of the IR spectrum covered. The most common design approach is to select a segment of the IR spectrum, optically filter the units to look only at that segment of the spectrum (Figure 7), and integrate the energy falling on the detector for that segment. Many general-purpose instruments use a wideband (e.g. 8 to 14 µm in Figure 7); because adequate energy is available, only low-gain amplifiers are required. Some inexpensive units cover most of the .7 to 20 µm IR spectrum, at the expense of being "distance-sensitive" because they include some atmospheric absorption bands. A thermometer which excludes these absorption bands (e.g., 8 to 14 µm) avoids these problems.

For special purposes, very narrow bands (2.2 µm in Figure 7) may be chosen. These instruments are costlier because more stable, high-gain amplifiers are needed to amplify the smaller signals which result from reduced energy levels in these narrow bands. However, they can also be used for general-purpose work, as well as special applications. The ability of narrow band instruments to measure low temperatures may be limited somewhat by the low energy levels encountered.

A third type of thermometer is the ratio, or two-colour thermometer. This instrument measures the ratio of energies at two selected narrow bands. If the change in emissivity at the two selected wavelengths is the same, the effect of emissivity is eliminated, with attendant advantages.

Further, the target need not fill the field of view, as is the case with single-colour instruments. If a target which just fills the field of view is cut in half, half the energy will be lost to the detector, and the single-colour instrument will read low. With the two-colour instrument, if the energy at both wavelengths is cut and the ratio stays the same, the temperature reading will not change (Figure 8). The benefit resulting from this feature is that if a cloud of dust or smoke obscures the target, the radiation reaching the thermometer may be reduced, but the reading will not change as long as the ratio of energies does not vary.

In practice, the emissivities at the two wavelengths may not vary in a similar manner. Two-colour thermometer manufacturers address this problem with a ratio calibrator adjustment, similar to the emissivity compensator adjustment of single colour instruments. This adjustment is used to calibrate the unit in much the same

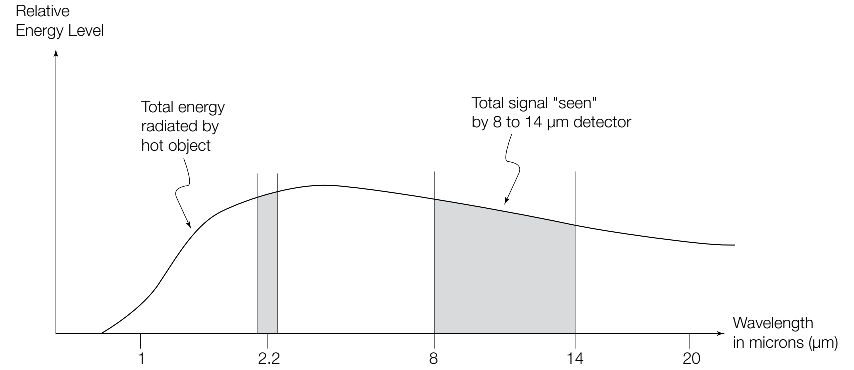

Figure 7: Distribution of energy as received by filtered IR detectors

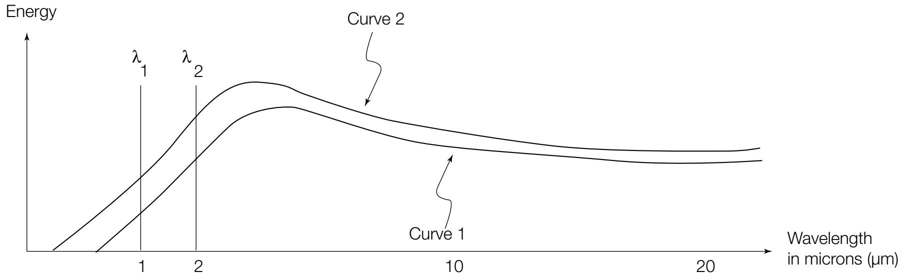

Figure 8: Two temperatures as interpreted by ratio (two-colour) pyrometer

manner described earlier for the emissivity compensator. However, this works only for that particular material, and often only around a given temperature. Therefore, unless the target is a true graybody, the ratio thermometer has questionable advantage over a single-colour unit.

In the event of reduced target area (by a target not filling the field of view, or being obscured by dust or smoke), a single colour unit can read properly by adjusting the emissivity compensator to make up for the loss. This adjustment can make up for any kind of loss in the system, provided the loss is constant. The ratio thermometer has an advantage only when the loss varies during the process, or in a situation where changing the emissivity adjustment is not feasible. If the adjustment needs to be made only once, the user need not spend the extra cost of a two-colour instrument.

To summarise, a two-colour thermometer is beneficial in measuring (1) graybodies of varying or unknown emissivity and (2) targets with a varying field of view due to changing size or distance, varying concentrations of dust or smoke or sight-window coating. Use of a two-colour instrument is justified economically only when special circumstances require it. Further, in some applications, performance can be less accurate than single-colour instruments if there are inconsistent emissivity ratios.

Spectrum For Low Temperatures (Below 500°C/1000°F)

The most popular band for general purpose measurements up to 500°C is 8 to 14 µm. This is a wide band, yielding sufficient energy even at sub-freezing temperature, and free from atmospheric absorption. Uses include maintenance diagnostics, all organic processes (paper, wood, rubber, textiles, agricultural), thick plastics, glass surfaces (if reflection from strong heat sources is not a problem), well-oxidised metals, and metals near ambient (if reflections don't interfere). This is the only type of IR thermometer suitable for measurements below ambient temperature.

Spectrum for Mid-Range Temperatures (100-800°C /200-1500°F)

One of the preferred shorter wavelength bands for penetration of atmosphere, flames and gases is 3.8 µm. This is the best compromise for low-temperature metals because shorter wavelength instruments are limited to high temperatures.

Spectrum for High Temperatures (Above 300°C /600°F)

Another window in the atmosphere and flame-absorption bands ideal for temperature measurement is 2.2 µm. This narrow band is especially well-suited for high temperature measurements.

Special Purpose Instruments

METALS: Metals present some unique IR temperature-measurement problems.

Foremost is the fact that most metals tend to be very reflective (unless well oxidised) and thus have low emissivities. Some of these emissivities are so low that a large portion of the sensed energy is reflected radiation (usually from heaters, flames, refractory walls, etc.). This can result in varying and unreliable readings. For most metals, the problem increases at the longer wavelengths.

The shortest possible measurement wavelength should be used. As shown in Figure 9, the emissivities of most metals improve as wavelength decreases.

Also, as illustrated by Figure 10, a smaller change in indicated temperature results from the same change in emissivity at shorter wavelengths, producing more accurate measurements when emissivity variations are present.

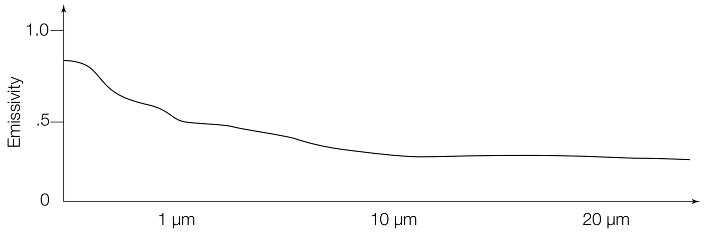

Figure 9: Typical metal: variation of emissivity with wavelength

Two factors limit how short the wavelength can be: (1) the lowest temperature which must be measured; as can be seen from blackbody radiation curves, the shorter the wavelength, the less energy is available at that wavelength, and (2) the width of the temperature range desired. As wavelength decreases, the energy level difference between two given temperatures increases, and an amplifier with wider dynamic range capabilities is required. At some point, the gain required to do this becomes unattainable. For these reasons, a compromise must be made; the shortest wavelength which allows the required temperature range should be used.

Other considerations in making this choice may be: instrument price and availability, presence of gases or flames in the line of sight, ability to see through vacuum chamber windows, etc. The optimum wavelength for high-temperature metals is the near infrared, around .8 µm. Other choices are 1.6 µm (where some metals have the same emissivity at different temperatures), 2.2 µm and 3.8 µm (both of which are recommended for reading through clean flames). If the metals are coated, well oxidised, or can be temporarily improved by adding a high-emissivity coating, 8 to 14 µm instruments can be used. Other compromises for low temperature metals are 3.43 µm and 5.1 µm.

Spectrum for Plastics

In general, plastics thicker than 2.5 mm can be measured using 8 to 14 µm instruments. In the case of thin films, however, plastic is partially transparent in the 8 to 14 µm band. Heat sources on the other side of the film and variations in the thickness will result in variations in the IR temperature reading.

Fortunately, there are certain resonant points in the IR spectrum at which thin films appear opaque to an IR thermometer due to characteristics of molecular bonding, eliminating the transmitted energy completely at certain wavelengths. Some plastics (polyethylene,

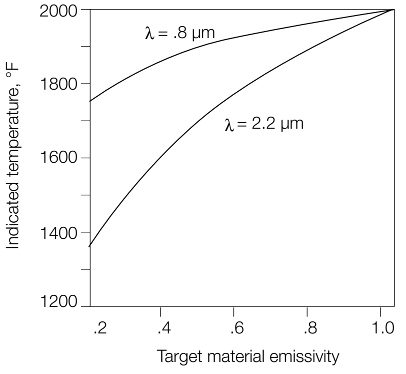

Figure 10. Readings obtained on IR pyrometers with centre wavelengths of .8 µm and 2.2 µm as actual emissivity of target material varies; target temperature is 1100°C, emissivity is 1.0.

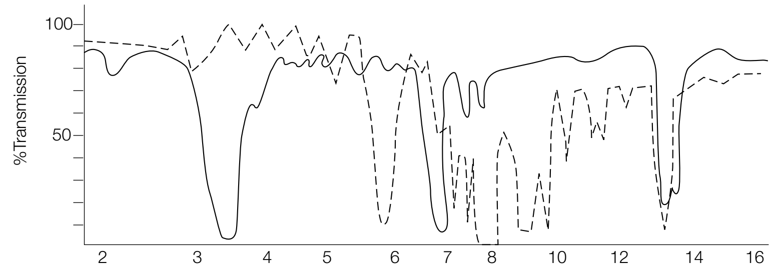

Figure 11: Solid line represents transmission characteristics of 25 µm polyethylene film (typical of plastics wtih strong 3.43 µm absorption) while dashed line illustrates 7.9 µm absorption of polyester film

polypropylene, nylon, polystyrene) are opaque at 3.43 µm; other plastics (polyester, polyurethane, Teflon, FEP, cellulose, polyamide) are opaque at 7.9 µm (Figure 11). Some films are opaque at both. In the latter case, a choice may be based on spectral reflectivity, instrument price and availability, or whether quartz heaters are used in the process (because these heaters may cause severe interference at wavelengths shorter than 5 µm). For plastics opaque only at 3.43 µm it may be possible to use the weaker, secondary 6.86 µm wavelength to avoid quartz heater interference.

Spectrum for Glass

The glass industry is one in which the different factors involved in IR measurement, particularly reflection and transmission, must be well understood for optimum results. Figure 12 shows the relationship of transmission to wavelength. In general, pane glass is opaque beyond 5 µm, and becomes progressively transparent at shorter wavelengths (as evidenced by the human eye). The .8 µm instrument measures several centimetres into molten glass, 2.2 µm about 75 to 100 mm. Instruments using 3.8 µm will measure no further than 25 or 50 mm, depending on the type of glass, so this wavelength is excellent for averaging “gob” temperatures. (These figures are for non-pigmented glass, and it must be remembered that glass nearest the surface will contribute the most to the temperature reading; pigmented glass will be more opaque, even at short wavelengths.) For panes, bottles, and other thin-wall glass, the longer wavelengths must be used. Reflection becomes critical at 8 to 14 µm; reflectivity averages 15%. This band can be used with emissivity settings of .85 with good results. Reflectivity is negligible between 5 to 8 µm but 5.1 µm is preferred as most of the temperature sensed is from a few mils beneath the surface, reducing the cooling effect of surface convection currents. The 5 to 7 µm band is discouraged unless the absence of steam and water vapour can be guaranteed (due to the 5.5 to 7.5 µm absorption band); 7.9 µm is ideal for surface measurement, with no reflectance.

Spectrum for Flame Measurement/ Combustion Optimising

While most IR instruments can be used to measure “dirty” flame temperatures, a clean flame (one with no particulate or smoke) can be measured at 4.5 µm where CO_2 and NOx are opaque, provided these by-products are present and the IR pathlength through the flame exceeds 25 cm. The same instrument can also assist in combustion optimising, even for smaller flames, because relative readings can be used (absolute readings are not required).

Fixed Mount and Portable IR Thermometers

Fixed mount instruments are generally installed in one location to continuously monitor or control a given process. They operate from the local power source (110/220 V AC or 24 V DC), are aimed at a single point or scan an area by a mechanical aiming device. Often they are supplied with a portable case and can be moved from one location to another. In manufacturing, a process can be studied by monitoring several points at different intervals. The sensing head can be mounted on a tripod, and the signal output fed to a chart recorder or data logger for later analysis.

If a truly portable unit is needed, battery-operated IR thermometers are available to match the features of nearly all fixed-mount instruments except control functions. One of the limitations of these units is the need for periodic battery replacement. Generally, their uses have been maintenance diagnostics, quality control functions, periodic spot measurements of temperature critical processes, and energy surveys.

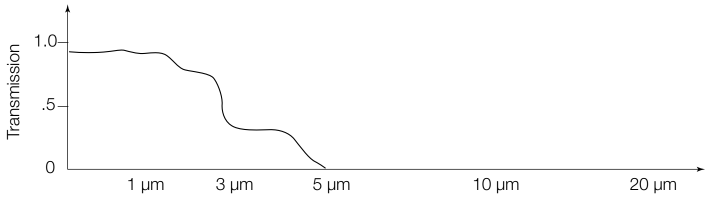

Figure 12: Transmission spectrum of glass (typical 3 mm pane glass)

Critical Specifications

In addition to optics, spectral response, emissivity, temperature range, and mounting (fixed-mount vs portable), the following list of items should be considered in selecting an infrared thermometer:

1. *Response time:* The instrument must respond quickly enough to process changes for proper recording or control of temperature. IR thermometers are usually faster than most other temperature measurement devices, with typical response times in the 100 ms to 1 s range.
2. *Environment:* The instrument must function within the range of ambient temperatures to which it will be exposed. Special provisions must be made to protect the instrument from dirt, dust, flames, and vapours. Intrinsically safe or explosion-proof instruments may be required.
3. *Physical mounting limitations:* The sensing head must fit in the space available to sight the object. If this is a hazardous location, risk can be minimised by using a head which contains the fewest parts (i.e., detector and ambient sensor only) so that a catastrophic loss does not require replacement of the entire instrument. This type of instrument typically uses a remotely located electronics box containing most of the circuitry, which can be mounted a safe distance away from a hazardous location. Alternatives include use of fibre optics, sight tubes, or front-surface mirrors to direct IR energy to the detector.
4. *Viewing port or window applications:* If a vacuum chamber, special atmosphere, or other process requires measuring temperatures through windows into vessels, care must be taken to ensure that the window will pass energy at wavelengths measured by the instrument. Glass will pass wavelengths shorter than 3 µm, quartz .5 to 4.5 µm, zinc selenide from 2 to 15 µm, germanium 4 to 14 µm. Irtran, a series of materials manufactured by Kodak, is available in several different band pass wavelengths from .5 to 20 µm.

   If visible sighting is required as well as infrared, a window material which transmits visible energy as well as infrared must be used. The temperature range of measurement dictates the longest wavelength to be passed, since peak energy wavelengths increase as temperature decreases.
5. *Signal processing:* Various signal processing devices are integrated to produce outputs to interface with displays, recorders, controllers, data loggers, and computers. Displays, alarm set points, and PC Interfces are commonly an integral part of the IR thermometer.

Signal processing features include:

Maximum reading: a stored value for the highest temperature measured.

Minimum reading: a stored value for the lowest temperature measured.

Difference: maximum minus minimum.

Average temperature: the mean of all temperatures measured in a given time period.

Variable time constant: enables smoothing displayed temperature or output in rapidly changing temperature measurements.

Integration of reflected energy compensation: allows calculation based on discrete input for unwanted energy received by instrument.

Output formats:

mV linear or nonlinear
mA linear
Thermocouple equivalents
RS-485
USB
Contact closures for preset alarm points
Self-test or diagnostic outputs.

Various accessories are available to make IR thermometers convenient to use and reduce installation costs. For portable instruments, accessories include: carrying case, wrist strap and calibration source. Fixed instrument accessories include: sight tube, air purge collar, water-cooled housing, mounting bracket, swivel bracket and alignment light spots.