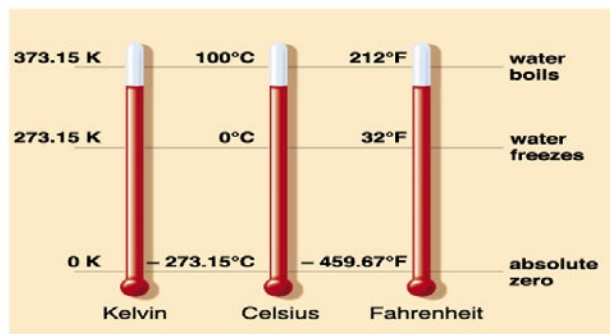


Infrared Basics

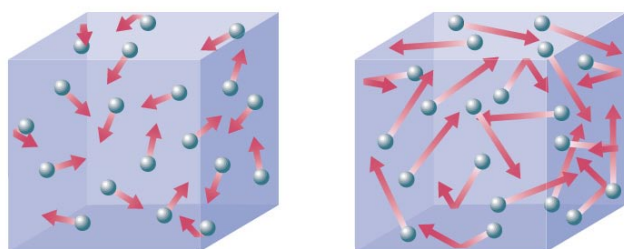
Infrared Energy, Emissivity, Reflection & Transmission

Thermal Energy and Infrared Emission

Heat is a form of energy. Heat energy is stored in matter (everything around us) just like electrical energy is stored in a battery. An object that contains no heat energy is very cold, and is said to be at absolute zero (-460 F or -273 C). This is the coldest anything can be, because it contains absolutely zero heat energy. As heat is added to the object, its temperature rises. The more heat energy an object contains the hotter the object becomes.



This heat energy is stored within matter through the movement of molecules and atoms (and subatomic particles). When an object is at absolute zero and contains no heat energy the molecules and atoms do not move. As heat energy is added and the temperature begins to rise, the atoms and molecules (and sub-atomic particles) begin to vibrate (and change energy states). As the amount of heat energy stored in the object increases, the vibration of the atoms and molecules becomes more vigorous.



Longer arrows mean higher average speed.

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Just as a sound is generated when two hands are clapped together or with the vibration of a rubber band, infrared energy is released by the vibration of these atoms and molecules - by the collisions when they bump into each other (and as electrons jump back down from a temporary elevated valence – returning back to their normal level after being bumped into a higher energy state by all of the thermal energy bouncing around). This released energy is the infrared energy that is measured by an infrared thermometer. The higher the temperature the more vigorous is the atomic and molecular vibration, and the more infrared energy is emitted. There is a very strong correlation between temperature and emitted infrared energy, and this is why an infrared thermometer can be a very accurate temperature measurement device.

Blackbody Energy Distribution vs. Wavelength & Temperature

In general terms, the total amount of infrared energy emitted by an object is proportional to temperature to the fourth power. Therefore, a relatively small change in temperature can represent a relatively large change in infrared energy. For this reason, infrared thermometers can be highly accurate. However, there are some issues that may influence the accuracy of an infrared thermometer. Therefore, it is helpful to examine the nature of infrared energy in greater detail.

As previously stated, infrared energy is emitted as a result of atomic and molecular vibration. When the object is cold these vibrations are relatively slow and the amount of energy released is relatively small. As the object becomes hotter, the frequency of the vibrations increases and the total amount of infrared energy increases significantly. The frequency of the vibrations is related to the wavelength of energy produced. The higher the frequency, then the shorter is the wavelength. In general, for most materials, infrared energy is not emitted at a single frequency or wavelength, but over a range of wavelengths pertaining to a distribution pattern similar to a lop-sided bell curve. As may be seen in the following figure, at any given wavelength the amount of infrared energy increases with an increase in temperature; however, the peak wavelength of emission is longer for lower temperature objects and shorter for higher temperature objects.

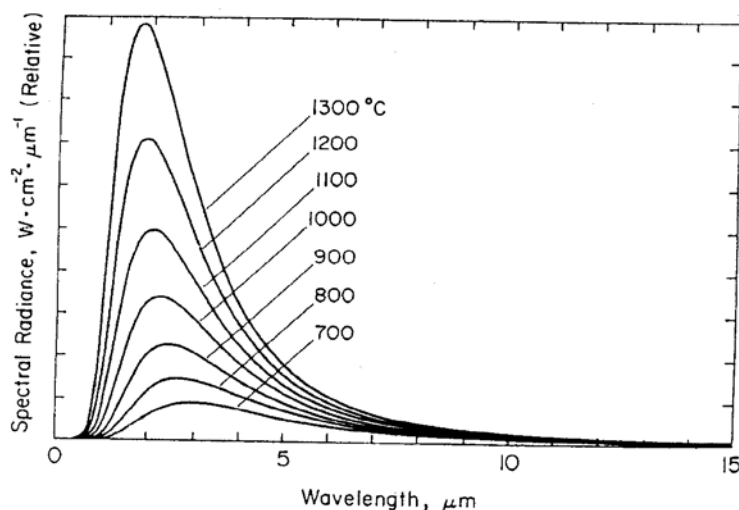


Figure 2 = Infrared Energy vs Temperature vs Wavelength Curve

There are two important points to note about the distribution of infrared energy for different temperatures across the wavelength spectrum. The most important point is to note that the change in infrared energy for any given change in temperature is much greater at the shorter wavelengths than it is at the longer wavelengths. This means that a short-wavelength infrared thermometer provides much more resolution, and is therefore much more tolerant of various interferences, such as emissivity change (more on that below), dirty optics and misalignment. The second important point is that the wavelength of peak energy emission increases as the temperature becomes lower and lower. This means that it is necessary to use a relatively long wavelength sensor when measuring exceptionally low temperature values. These issues will be discussed in greater detail in following sections.

Definitions of Emissivity (Blackbody, Greybody, Non-Greybody, Selective Emitter)

At first glance the determination of temperature based upon infrared energy emission would seem straight forward. High temperature objects emit a lot of infrared energy, and low temperature objects emit less infrared energy. In theory, the temperature value may be determined with great confidence by simply measuring the amount of infrared energy emitted. In practice things are not always so easy. This is because the amount of infrared energy emitted by an object is not a factor of temperature alone. There is another parameter, called emissivity (or the tendency to emit) that must be considered. The emissivity value of an object is influenced by the material, its surface condition, its reflectivity and its opacity. This fact sometimes complicates the temperature measurement process considerably. The understanding of emissivity and its character is therefore an essential component to properly applying an infrared thermometer.

Scientific Definition of Emissivity and Blackbody.

A physicist defines emissivity as the percent of infrared energy emitted by an object at any given temperature as compared to the theoretically perfect amount of infrared energy emitted by an object at the same temperature. In other words, the emissivity of an object is the ratio of the actual amount of infrared energy emitted compared to the theoretically perfect amount that could be emitted. This is a number between 0.000 and 1.000. An object that emits the theoretically perfect amount of infrared energy at any given temperature is called a blackbody. A blackbody is a perfect emitter. Because it emits 100% of the theoretical amount of infrared energy, it has an emissivity value of 1.000. An object that emits only 60% of the theoretical amount of infrared energy has an emissivity value of 0.600.

The amount of infrared energy emitted by a perfect blackbody at various temperatures and wavelengths has been well-documented and well-understood for hundreds of years, and is one of the basic properties of general physics. When an infrared thermometer is manufactured it is

calibrated against a blackbody emitter. When it is used in the field it must account for the emissive character of the measurement condition. For applications closely approximating blackbody conditions virtually any infrared thermometer will yield accurate results. For applications that deviate significantly from perfect blackbody conditions the selection of the most appropriate infrared thermometer, and the issues associated with its installation, can become critically important. The challenge is in understanding the emissive nature of each measurement application of interest.

Practical Definition of Emissivity

While the scientific definition of emissivity is important to understand, it is not very helpful when it comes to understanding the nature of emissivity for real-life applications. Before a more practical definition of emissivity may be provided it is first necessary to introduce some basic concepts.

For a unit volume in free space (for non-engineers, this means a block of material that is not being acted upon by anything other than what I am about to explain) under isothermal steady-state conditions (this means that it is of uniform temperature and the temperature is not changing over time), 100% of infrared energy directed towards the unit volume is either reflected, transmitted through, or absorbed.

$$\% \text{ Reflected} + \% \text{ Transmitted} + \% \text{ Absorbed} = 100\%.$$

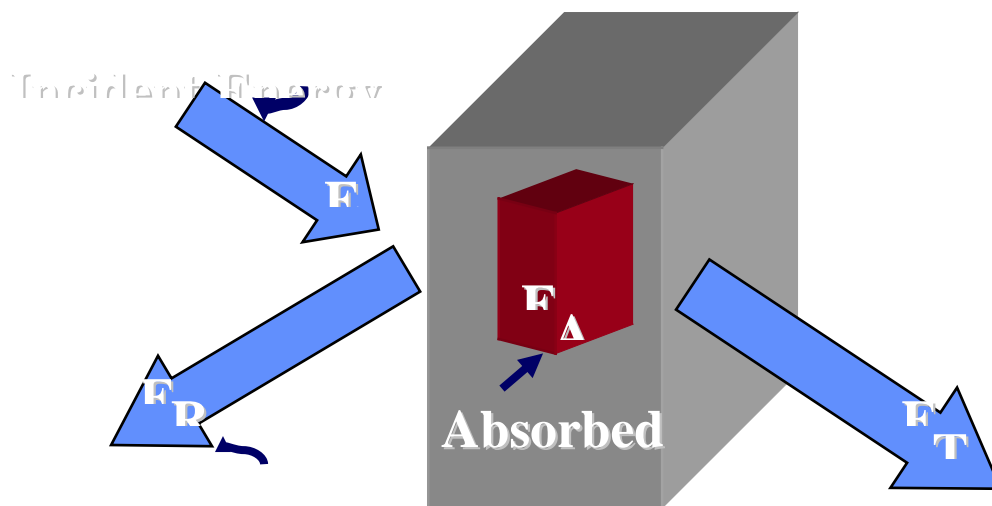
If the object is assumed to be opaque, then the amount transmitted through the object is zero. Therefore, $\% \text{ Reflected} + \% \text{ Absorbed} = 100\%$.

If the object were to absorb infrared energy (thermal energy), then its temperature would increase. Because the object is at steady-state (its temperature is not changing), it must be emitting energy at the same rate that it is absorbing energy. Therefore, $\text{Absorption} = \text{Emission}$.

$$\% \text{ Reflected} + \text{Emissivity} = 100\%.$$

Subtracting reflectivity from both sides of the equation, $100\% - \% \text{ Reflected} = \text{Emissivity}$.

Therefore, for any opaque object, emissivity is the opposite (reciprocal) of reflectivity, and $\text{Emissivity} + \text{Reflectivity} = 100\%$. Similarly, for translucent objects, $\text{Emissivity} + \text{Reflectivity} + \text{Transmission} = 100\%$.



Reflective Energy

In other words, for opaque objects, emissivity and reflectivity add together to be 100%. If an opaque object is 10% reflective, then it is 90% emissive, and has an emissivity value of 0.900. If an opaque object is 60% reflective, then it is 40% emissive, and it has an emissivity value of 0.400. This definition of emissivity provides a more practical tool for understanding emissivity and for applying infrared thermometers, as reflectivity is something that is readily measured and understood.

Perhaps the most misunderstood aspect of emissivity is that there is no one emissivity value for most materials. Although the measured material is one factor associated with the emissivity of a surface, other factors often contribute a more significant influence, including surface texture, degree of oxidation, micro-structure, and surface contamination or coatings. These issues are factors because they influence the reflectivity of the surface of the material. The emissivity of molten steel is very different from the emissivity of solid steel, and the emissivity of hot-rolled steel is very different from the emissivity of cold-rolled steel. Another misunderstanding is the role of color. Countertop laminations (Formica brand, for example) come in all colors, but the emissivity value of a countertop is unaffected by the color changes. Instead, it is the texture of the surface that dictates the emissivity value. High-gloss surfaces have a lower emissivity than do low-gloss surfaces. Tables and charts are widely available that identify the emissivity value for a wide range of materials. Unfortunately, most of these documents are misleading and inappropriate.

Blackbody Materials

An object that emits the theoretically maximum amount of infrared energy at any given temperature value is called a blackbody material. A blackbody material is a perfect emitter, and has an emissivity value of 1.000, or 100%. Because the emissivity value of a blackbody material is 100%, a perfect blackbody material is completely non-reflective. Materials that are non-reflective are

more highly emissive, and more closely approximate perfect blackbody conditions. Therefore, highly non-reflective materials like paper, textiles, cement and bricks are relatively easy to measure with accuracy using a simple, general purpose infrared thermometer because these materials closely approximate perfect blackbody conditions. While many non-reflective materials approach blackbody conditions, many materials do not – especially those that are reflective or translucent. Materials that do not approximate blackbody conditions are categorized in one of three ways, depending upon their emissive nature. Different types of non-blackbody materials include greybody materials, non-greybody materials, and selective emitters.

Greybody Materials

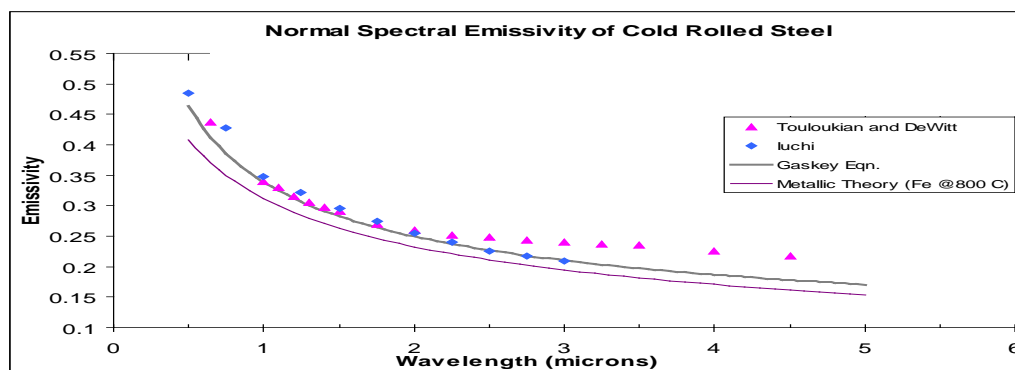
A greybody material is one that has an emissivity value less than 1.000, or 100%, and one for which the emissivity value is equal across all measured wavelengths. A greybody material may have a constant emissivity value, or the emissivity value may vary (usually as a result of changing surface roughness), but if it does vary, the value remains the same across all wavelengths. A greybody material that emits 70% as much infrared energy as would a perfect blackbody material at the same temperature has an emissivity value of 0.700. Generally speaking, opaque materials that have a reasonably high emissivity value (typically less than 30% or 40% reflective, so emissivity values higher than about 0.600 or 0.700) usually are greybody materials.

Non-Greybody Materials

A non-greybody material is one that has a different emissivity value at different wavelengths. For opaque materials the tendency for the emissivity to vary with wavelength is typically due to the physical size of the microscopic surface features of the material. For non-greybody materials, the tendency of the material to absorb, reflect or transmit infrared energy varies with wavelength. Non-opaque non-greybody materials called selective emitters are discussed in a separate section below.

An examination of surface texture and oxide formation will help to provide some insight about the emissive nature of materials. Although we think of reflective materials as highly smooth, when viewed under a microscope the surface has very small nooks and crannies. When these nooks and crannies are small enough so that the infrared wavelengths will not fit in, then the material is highly reflective at that wavelength. However, if the wavelength is small enough to fit into the nooks and crannies, then it can bounce around in there, and the material becomes less reflective. The emissivity is higher at the wavelengths where the material is less reflective, and it is lower at the wavelengths where the material is more reflective. Because the short wavelengths fit into the small nooks and crannies better than do the long wavelengths, the emissivity of highly reflective materials is generally higher at shorter wavelengths than at longer wavelengths. In general, if the emissivity value is below about 0.4 or 0.5, then the metal is a non-greybody for this reason.

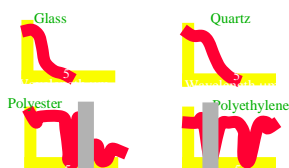
In addition to surface texture, oxide growth can also cause wavelength-dependent emissivity variation. If the oxide structure is large compared to the infrared wavelength, as with iron oxide, for example, then the surface appears to be rough, the emissivity is relatively high, and all wavelengths are emitted and reflected equally. If the oxide structure is very small on the scale of an infrared wavelength, as with thin layers of chromium oxide, for example, then, as with the small nooks and crannies above, the oxide growth can affect short wavelengths differently than long wavelengths. As the oxide layer grows thick enough to be optically diffuse at all wavelengths, then the emissivity value becomes equally high at all wavelengths. Thin films of very fine oxides are often too thin to be opaque, and so these coatings often affect the surface texture and also to act like a selective emitter.



Selective Emitters

Infrared energy is an electromagnetic energy, just like visible light, radio waves, and x-rays. If I shine a flashlight at my chest it does not go through, but if I shine an x-ray at my chest it goes right through. The only difference between visible light and x-rays is the wavelength. So, by changing the wavelength of measurement, some objects may be more or less transparent at some wavelengths, and more or less opaque at others. Glass is a good example of this. Glass is transparent at short wavelengths, but is opaque at wavelengths longer than about 4.8 microns. Because glass is highly transparent at short wavelengths, this means that thin glass has a low emissivity value at short wavelengths. Because glass is highly opaque at long wavelengths, this means that glass has a high emissivity value at long wavelengths. The reflectivity of glass varies with wavelength, too. Glass is both opaque and highly non-reflective at wavelengths between about 6.6 and 8.2 microns, and so this is the wavelength band where glass has the highest emissivity value and where glass most closely approximates a blackbody material.

Thin film plastics are the classic example of selective emitters. These materials are made up of long chains of hydrogen and carbon atoms. The repetitive and uniform molecular structure of these materials means that the molecules and atoms all vibrate with a uniform series of harmonic frequencies. Infrared wavelengths coincident with these harmonic frequencies are preferentially absorbed (not reflected or transmitted) by the plastic material, and conversely, these materials emit infrared energy preferentially at the wavelengths coincident with these harmonic frequencies. When we look at a plastic sandwich bag we can see right through it, but if our eyes were filtered at 3.43 microns, which is the harmonic frequency for the H-C atomic bond, then the sandwich bag would appear completely opaque. When measuring the temperature of a selective emitter it is critical that a wavelength be selected to coincide with a strong emission band. This is a wavelength where the infrared emissions approach blackbody conditions, and where the material is highly opaque and non-reflective. Other examples of selective emitters are all gasses, and all highly transparent materials. Many crystalline materials, such as silicon and engineered ceramics, are also selective emitters. The uniformity and geometry of the molecular structure dictates the emissive nature of the material.



Thin film coatings also act like selective emitters. In the metals industry, metal strips are often coated with a thin film. Oil-based paint, water-based paint, oil and wax are all examples of thin film coatings that can act like selective emitters. These materials are highly transparent at some wavelengths, and they are highly opaque and non-reflective at other wavelengths. The emissivity of the coated material is therefore highly influenced by the wavelength of measurement. The optimum wavelength of operation for an infrared thermometer will vary depending upon the coating material, the thickness, the required temperature range, and the need to view the coating or to view through the coating.

Optics and Alignment

An infrared thermometer collects infrared energy from within a conical field-of-view. This field-of-view is dictated by the active diameter of the sensor lens, the optical resolution and the focal distance. The area of measurement is the area projected on the measured target by this conical field-of-view. The area of measurement is typically circular or elliptical, but may be square or rectangular for some specialty applications. The sensor may include a traditional lensed configuration, or it may have a fiber-optic configuration. The sensor may provide no alignment aide, through the lens aiming, or aiming may be specified by a laser pointer or LED projection.

There are several terms that are used almost interchangeably by the industry to identify the area that the sensor is viewing. Field-of-view is a term that describes the three-dimensional volume within which the sensor is able to collect infrared energy. When the sensor is aimed at an opaque target, the sensor is not able to collect infrared energy from within the field of view beyond the opaque target. The area of measurement projected on the opaque target is commonly referred to as the “measurement spot” (or “spot” for short), the “viewing area,” the “target area,” or the “projected field-of-view” (or “field-of-view” for short). These terms are all used interchangeably.

Fiber Optic

Optical fibers are manufactured from glass or quartz, allowing short wavelengths to transmit freely. However, the long-wavelength sensors are not available in a fiber optic configuration because these

common fiber materials are opaque at the longer wavelengths. Exotic flexible fibers or rigid light pipes are available to transmit longer wavelengths, but they are expensive and / or fragile.

The fiber optic cable serves to couple a remote lens to the infrared thermometer. The infrared detector remains in the sensor housing, and the fiber cable channels the infrared energy from the remote lens to the infrared detector. Common fiber cables contain hundreds of individual transmitting fibers. These small fibers bend easily, and are protected by an outer sheathing. The fibers may be packaged in any number of ways, depending upon the application requirements. Some fiber cables are very small in diameter and nonconductive. These may be used in tight spaces and within heavy electrical fields. Other fiber cables are large, 2-3/4-inch diameter packages designed to protect the fibers from hostile environments. Traditional fiber cables are packaged within 1/4-inch stainless steel mono-coil, and some manufactures seal this with a protective outer jacketing.

Focusing and Distance Sensitivity

A brightness sensor provides an average temperature measurement of the area viewed. Therefore, the measured target must be larger than the area viewed. Because the diameter of the field-of-view varies with the distance from the sensor, the viewing distance is sometimes limited, but so long as the target is larger than the area of measurement, most quality sensors are distance independent. However, some lesser sensors exhibit distance sensitivity due to atmospheric interference or due to poorly designed optical systems. For most modern sensors, so long as the measured target is larger than the area of measurement, changing the focal point serves only to control the angles of convergence and / or divergence as the optical path travels away from the sensor.

A ratio sensor is unique in that it is able to provide an accurate temperature measurement of a target smaller than the area of measurement so long as the background temperature is significantly lower than the target to be measured. When using a ratio sensor to measure a target that is smaller than the field-of-view, the measurement must be made within the focal plane. The focal plane is a distance in front of and behind the focal distance within which the image is in focus. Similarly, if there is an optical obstruction, then it is best for this obstruction to be within the focal plane. The issue with objects or obstructions outside of the focal plane is that the two wavelengths produce a target area of slightly different sizes at the two different wavelengths when the image is out of focus. For high quality optical systems the focal plane can be quite deep. For example, when focused at a 5 foot distance the focal plane typically extends from about 2 feet to about 30 feet. As the sensor is focused closer to the sensor the depth of the focal plane becomes smaller and smaller. When focused at a 12 inch distance, for example, the focal plan is reduced to between 8 inches and 20 inches. Because this is an issue that affects only the edge of the image, this is more of an important issue for targets or obstructions at the edge of the field-of-view, and this is a less critical issue for targets or obstructions towards the middle of the field-of-view. When viewing through a long, slender tube, it is best to focus the sensor at the end of the tube in order to prevent or minimize any optical interference.

Viewing Tubes and Stray Infrared Energy

Viewing tubes are commonly used to mount an infrared thermometer when viewing into a furnace or chamber. It is a common misconception that these tubes also prevent stray reflections from being viewed by the sensor. While these tubes may do well to prevent airborne contaminants from passing through the field-of-view, they usually provide no benefit against stray infrared energy.

In order for stray infrared energy to be seen by the sensor the energy must travel from within the field-of-view and into the sensor's lens. Stray energy originating from outside of the field-of-view can only enter the sensor lens if it first reflects off the measured target within the area of measurement. These viewing tubes provide protection against stray infrared energy only if they prevent the stray energy from striking the area of measurement at an angle which will lead to a reflection into the sensor lens. To perform this function effectively, the tube outer diameter must be larger than the diameter of the measured area plus twice the distance from the target.

Alignment and Angle of Incidence

A common misconception is that infrared thermometers work best when viewing the measured target at a normal (3D perpendicular) angle. While it is not necessary to measure from a normal angle, it is best to measure within the cone of maximum emissivity. The infrared energy emitted by a surface is not equally emitted in all directions. For most materials, when the surface is viewed within a 60-degree cone from normal the emissivity is the highest. As the viewing angle increases from normal (decreases towards parallel) the emissivity drops – sometimes dramatically. For molten metals the emissivity is the highest within a 45-degree cone (1/2-angle). For materials with a rough surface the emissivity is highest within a 85-degree cone (1/2-angle). For most smooth materials the emissivity is highest within a 60-degree cone (1/2-angle).

ESP Signal Conditioning