

## What is Infrared Heating?

All bodies above zero temperature ( $-273^{\circ}\text{C}$ ) emit infrared radiation in the form of waves which pass through space and are partly absorbed by bodies they strike. This radiation forms a part of the electromagnetic spectrum and has the strongest heating effect of all. The nature of the radiation is the same in essence as that of x-rays, ultraviolet, visible light and radio waves.

It has been known since the mid nineteenth century that infrared radiation, or group of rays, behave in a similar manner to visible light as far as transmission, reflection and absorption are concerned. The concept of radiation is not easy to define, as both corpuscular and oscillatory aspects are involved.

The electromagnetic energy that is emitted from the surface of a heated body is called thermal radiation, and consists of a continuous spectrum of frequencies extending over a wide range. The spectral distribution and the amount of energy radiated depend chiefly on the temperature of the emitting surface.

Careful measurements show that for a given temperature there is a definite frequency at which the radiated power is maximum. Furthermore the frequency of the maximum is found to vary in direct proportion to the absolute temperature. At room temperature, for example, the maximum occurs in the far infrared region of the spectrum and there is no perceptible visible radiation emitted. But at higher temperatures the maximum power is radiated at correspondingly higher frequencies, and at about  $500^{\circ}\text{C}$  a body begins to glow visibly. The rate at which energy is radiated by a hot body is also found to be dependent on temperature.

Electromagnetic radiation is created by oscillatory electric charges, and the frequency of oscillation determines the kind of radiation emitted. Radio waves and microwaves exist at the lower frequencies and x-rays and gamma rays exist at the higher frequencies. In between these is a range of frequencies known as the optical spectrum, with infrared, visible light and ultraviolet light.

The optical spectrum is characterized by the fact that the radiation can be directed, focused and controlled by mirrors and lenses and that prisms and gratings can be used for dispensing it into a spectrum.

Ordinary sources of radiation in the optical spectrum, such as tungsten filament lamps, fluorescent lamps and flames consist of a very great number of molecules which have electric charges that oscillate independently of each other, producing a range of frequencies.

Unlike these sources, excited individual atoms and molecules give out radiation at various discrete frequencies, which are characteristic of the particular kinds of atom or molecules involved. The optical spectra of most atoms are quite complex, but a few elements such as the hydrogen and the alkali metals have relatively simple spectra.

The most simple of all is the hydrogen atom which consists of an electron and a proton. The electron may be considered as being able to inhabit only certain levels about the proton and to move from one level to another it needs to gain or lose an amount of energy, called a quantum.

Small quantities of energy are measured in electron-volts (eV), and for radio waves a quantum is about  $0.000004$  eV, for infrared a quantum is about  $0.004$  eV, and for x-rays and gamma rays it is about  $40,000$  eV.

When an electron moves to a lower energy level a discrete amount of energy in the form of a photon is emitted from the atom. This photon takes the form of electromagnetic radiation. Movement between the lowest levels produces a photon of far ultraviolet, movement between the next lowest levels produces visible light and near ultraviolet; movement between the middle levels produces infrared.

A photon may be considered as having a cross sectional area, like that of a ball; the larger the ball the greater the chance of it hitting something. Similarly, atoms and molecules can be considered as having a cross sectional area and materials made of larger atoms and molecules are likely to absorb photons more quickly than materials made of small ones. However, materials absorb infrared selectively. Virtually all transparent solids show broad absorption bands that extend into the visible frequencies.

## Reflection, Absorption and Color

Solids have atoms that are fixed in position relative to each other, and each atom has electrons that are tightly bound to it. These are known as polarization ions.

A low frequency electromagnetic field falling on the surface of a solid would cause the electrons near the surface to become more energetic and to oscillate at the applied frequency. After a time of perhaps less than a second the energy is given off as a photon.

The solid does not absorb energy unless the frequency of the electromagnetic field is close to the resonant frequency of the electrons. At this frequency the magnitude of the electrons' oscillation is sufficiently large for them to "bump" into one another electrons, so the solid gains energy.

An electromagnetic wave always transports the same amount of energy per second. When the wave enters a solid the increase in the electrons' oscillations causes the energy density to increase, so the wave travels more slowly. An electric field is set up by the oscillating electrons and this causes a part of the electromagnetic field to be reflected.

Materials made only of atoms with only tightly bound electrons absorb very little energy. They are good insulators.

In many solids some of the electrons are not tightly bound, and some solids contain electrons that can move freely. These are called conduction electrons. An electromagnetic wave causes conduction electrons to oscillate in anti-phase with it, and this decreases the wave's energy density. The wave cannot increase its velocity so energy must be reflected. The electrons screen the solid, and it takes only a few conduction electrons to reflect the wave totally.

The polarization electrons resonate at frequencies in the infrared and visible radiation bands and energy from infrared and visible electromagnetic waves is absorbed by solids at these frequencies.

At higher frequencies the conduction electrons undergo smaller and smaller oscillations, so the wave penetrates more deeply.

As the frequency increases through the visible range and the penetration increases the overall absorption before the wave is completely reflected stays roughly the same. This is why most metal looks grey and not blue or red. The higher conductivity of a solid the more light it reflects and the whiter it appears.

Very white surfaces are usually prepared from very transparent materials powdered into small particles. The light entering the particles is reflected by the randomly oriented surfaces

A solid appears a certain color because it reflects one part of the optical spectrum preferentially to another part. A paint achieves its color by mixing a fine transparent powder with other particles which absorb particular frequencies in the visible spectrum. To make colored films the transparent powder is omitted.

To assess the reflection and absorption properties of paints, coatings and nonmetallic solids in the infrared spectral region it will always be necessary to rely on empirical measurements. Properties vary not only with chemical composition but also with fine structure, surface roughness and temperature. Where objects are heated with short wave infrared lamps as much as 20% of the radiation can be in the red end of the visible spectrum. This inevitably leads to blue paints absorbing more radiant energy than red paints.

## Laws of Radiation and Their Practical Significance

Turning now to the oscillatory nature, the radiation passes through successive identical states at precise time intervals measured in seconds. The rate at which the states recur, or frequency, is measured in cycles per second so that frequency is equal to the reciprocal of time. The velocity of propagation (in a vacuum) for all radiation is  $3 \times 10^8$  meters per second: the speed of light. From this we can deduce that the distance between successive identical states -- the wavelength -- is the product of velocity and time. See figure at right.



*Expressing these statements mathematically,*

$t$  = time interval in seconds which separates the passage of radiation through two successive identical states

$f$  = frequency in cycles per second

$\lambda$  = wavelength in meters per second

$V$  = speed of light in meters per second

*We have:*

$$f = \frac{1}{t}$$

$$\lambda = Vt = \frac{V}{f}$$

Infrared and visible wavelengths are normally expressed in microns (or micro-meters), this unit being one millionth of a meter. Radiation visible to the human eye occurs over a very narrow band, from 0.4 to 0.76 microns. The broad region occupied by infrared extends from 0.76 microns (that is just beyond the red end of the visible end of the spectrum) to 400 microns. However, the radiation used for process heating occurs between wavelengths of 1 and 5 microns in order to obtain adequate source temperatures. This represents a temperature range of 2200 °C to 300°C.

Continuing well beyond the infrared or thermal region to much longer wavelengths of the order of centimeters and meters,

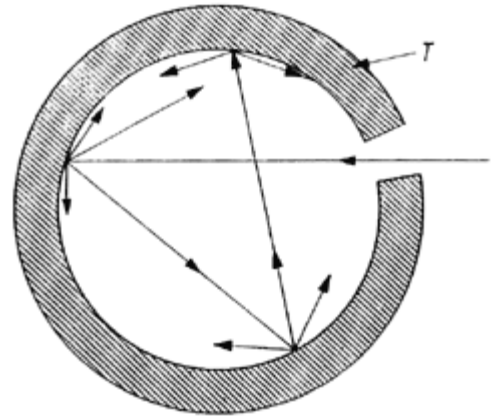
the spectrum is occupied by microwave, radar, television and radio communications equipment.

The radiation emitted by a body can be determined if the temperature and nature of its surface (emissivity) are known.

These are the key parameters required to calculate the radiation emitted by a surface at a particular wavelength or over a band of wavelengths.

the starting point in the discussion on the laws of thermal radiation is the concept of the "black body" or Planckian radiator. This is an ideal body which totally absorbs all incident radiation at all wavelengths. The reflectivity is therefore zero (Note that the term "black body" does not have any color connotation in the visual sense). In addition to being a perfect absorber, it is also a perfect radiator: it will radiate the maximum amount of energy at any given temperature. This concept is very convenient in the mathematical and graphical treatment of infrared theory and the development of relationships.

A near approximation to the black body is provided by an isothermal enclosure (see graphic at right), which represents a hollow metal sphere with a small radial hole through its wall. Any radiation entering this hole undergoes multiple internal reflections and absorptions until total absorption is achieved. Conversely, if the sphere is heated, the hole will radiate as if it were a black body. This applies even if the sphere is heated to an incandescent temperature.



From this theoretical phenomenon, it is possible, for example, to visualize the interior of an enclosed furnace with all the walls at a constant temperature behaving almost as a black body. However, in practice all bodies are less than perfect radiators or absorbers, and are therefore referred to as "grey bodies," or more strictly "nonblack bodies." The maximum radiation intensity  $W$  produced by a black body unit interval of wavelength is obtained from Planck's Law:

$$W_{\lambda, T} = \frac{C_1}{\lambda^5 \left( \exp \left[ \frac{C_2}{\lambda T} \right] - 1 \right)}$$

The expression "exp" is usually very much greater than unity so that Planck's Law can be written:

$$W_{\lambda, T} = C_1 \lambda^{-5} \exp - \left[ \frac{C_2}{\lambda T} \right]$$

Where:

$W_{\lambda T}$  = emission at wavelength  $\lambda$

$C_1$  =  $3.741 \times 10^{-16}$  W/m<sup>2</sup>

$C_2$  =  $1.439 \times 10^{-2}$  mK

$\lambda$  = wavelength in microns

$T$  = absolute temperature

In practice this formula is seldom used in the process heating field as total emission is a more meaningful quantity. The total emission from a black body is obtained by integrating Planck's Law for all wavelengths. This is known as the Stefan-Boltzmann Law:

$$W = \sigma T^4 \text{ (W/m}^2\text{)}$$

$$\text{where } \sigma = 5.67 \times 10^{-8} \text{ (Wm}^{-2} \text{K}^4\text{)}$$

$\sigma$  is known as the Stefan Boltzmann constant.

It will be seen from the Stefan-Boltzmann Law that the total energy radiated by a black body is proportional to the fourth power of the absolute temperature. For example, by doubling the absolute temperature of a black body the total radiated energy increases, theoretically, by a factor of sixteen. Although the radiation at all wavelengths increases, the bulk of the excess is at the short end of the spectrum.

The emission from a surface of a nonblack body is always lower than that from an ideal black body, the ratio which relates the two values being known as the emissivity of the surface.

If  $E$  = emissivity ( $E < 1$ )

$W_{NB}$  = emission from a nonblack body at temperature  $T$

$W_B$  = emission from a black body at temperature  $T$

then

$$E = \frac{W_{NB}}{W_B}$$

Using the term  $E$  in the Stefan Boltzmann formula above, we obtain the emission for a nonblack body:

$$W = ET^4 \text{ (W/m}^2\text{)}$$

and for a body of area  $A$ ,

$$\text{Radiant heat} = A \times E \times T^4 \times \sigma \quad W$$

The equation above shows that the total radiation is directly proportional to the surface area of the emitting surface, an important factor in oven design.

the value of the emissivity is strictly wavelength dependent, but for practical purposes it is taken as being constant. Again, by doubling the absolute temperature the total radiation increases sixteen fold.

At best only 1% or 2% emission or absorption of radiation is possible with these metals unless they are alloyed or contaminated with more noble elements. However, the emissivity value for metals normally increase with temperature, the relationship being substantially proportional. Nonconductors usually have much higher values of emissivity at lower temperatures but they can fall with rising temperatures, in certain cases by an inverse ratio.

Absorption characteristics are defined in a similar manner to emission characteristics. The absorptivity of a nonblack body is the ratio of the nonblack absorption to the black absorption at the same surface temperature.

The absorptivity of a grey body is equal in value to its emissivity, a grey body having constant spectral emissivity at all wavelengths. Absorptivity values are often assumed to be constant as this helps to simplify oven design problems. This is true only if the source and workplace temperatures do not alter substantially during operation. However, if a different temperature were to be considered particularly if there is a major change in the source temperature, a new value of absorptivity might well be applicable, as shown earlier for emissivity.

## Wien's Law

The relationship between the absolute temperature  $T$  of a heat emitting body and the peak wavelength of emission,  $\lambda_m$ , is given by Wien's displacement law:

$$\lambda_m T = \text{constant}$$

If  $\lambda_m$  is expressed in microns

$$\text{Then } T\lambda_m = 2898$$

An important aspect of this effect is that as the temperature of an emitter is changed, for example, by varying the supply voltage, the peak wavelength of emission changes in inverse ratio. Therefore, as the temperature increases the peak wavelength decreases and vice versa.

For example, an emitter operating at a typical temperature of 2200 °C (2473K) would have a radiation peak at 2898/2473 = 1.17 microns, whereas an emitter operating at 650 °C (923K) would have a radiation peak at 2898/923 = 3.14 microns.

We therefore have a means of selecting an emitter whose emission spectrum is best matched to the absorption spectrum of a receiving body wherever this is a critical factor in optimizing the rate of heat transfer. It should be remembered, however, that in the infrared process heating field the transmission and absorption wavebands are usually sufficiently broad to utilize the side-bands of the emitted radiation in addition to the peak wavelength. The basic types of emitters which have become established over many years in industrial process applications are designed to operate within defined limits of temperature determined by their construction and materials.

## Reflectivity

This is defined as the fraction of the incident radiation which is reflected by a surface. It therefore makes no immediate contribution to the heating at the surface. The property of reflection is however used extensively in infrared heating both to orientate the energy and to provide enclosures in which the radiant energy can also take indirect paths to the surface requiring to be heated.

## Transmissivity

This is defined as the fraction of the incident radiation which is transmitted through the receiving surface. Many substances, particularly those in the liquid and gaseous state, transmit infrared. Thickness of the layer is an important factor. As illustrated by the greenhouse effect, transmission of visible and short wave energy does not necessarily extend to the longer wavelengths.

## Accounting for Total Radiation

Infrared radiation striking a body is dispersed in three ways: by reflection, absorption and transmission. The summation of these three quantities is equal to the value of the incident radiation, but it is normally the aim in infrared process heating to make the value of the absorbed radiation as high as possible.

## Lambert's Cosine Law

This is one of the basic laws of photometry which states that the intensity of radiation falling onto a flat surface from a small radiant source is a maximum when the receiving surface is normal to the source. However, if the receiving surface is turned away from the normal by an angle  $X$ , the intensity of the radiation received is proportional to the cosine of the angle  $X$  between the normal to the receiving surface at that point and the direction of the radiation.

This law applies only to a small source radiating over a relatively large distance, for example in illumination engineering. In infrared engineering the sources usually occupy substantial areas, sometimes larger than the individual receiving surfaces of the workpieces and the distances between the source and receiver are usually comparatively small. The cosine law is therefore not universally valid in the process heating field, but it does underline the need to arrange for the radiation to strike the receiver at right angles for the best efficiency of heat transfer. Conversely, if a thin metal panel, for example, is placed with its edge towards the source of radiation (that is, when  $\cos X = 0$ ) it would not, in theory, receive any heat. However, this directional effect does not present a problem in a well designed infrared oven, and in certain cases it can even be put to good use.

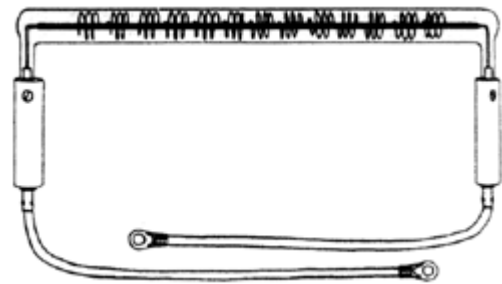
## The Inverse Square Law

This law is also based on the concept of a point source of radiation and is more appropriate to illumination engineering. It states that the radiant intensity at a receiving surface varies inversely as the square of its distance from the point source of radiation. On the other hand, radiation between two infinitely large parallel plates is independent of the distance between them. Another example not conforming to the Inverse Square Law is that of radiation to a sphere from a larger spherical shell surrounding it. For comparatively large radiant source areas such as those commonly employed in infrared ovens the surface-to-surface relationship between distance and intensity is found not to conform to the inverse square law. In practice the intensity can be almost independent of distance over very small distances of the order of a few centimeters, increasing to an almost linear relationship at greater distances.

## Tungsten Halogen High Intensity Emitters

As with the basic short wave emitters, the tungsten halogen units comprise a linear coiled tungsten filament surrounded by a clear quartz glass tube (see right).

However, with the basic type the tungsten slowly evaporates from the filament when the emitter is in use. This causes progressive blackening of the inner walls of the tube causing a steady loss of short wave output. The addition of a halogen such as iodine or bromine to the gas-filled tube prevents this blackening by combining with the tungsten particles to form a tungsten halide. This would normally condense on the inner wall of the tube, but if the wall is maintained above  $300\text{ }^{\circ}\text{C}$  it will not condense, but will be returned to the vicinity of the filament. The high temperature of the filament causes the tungsten halide to break down into tungsten and halogen. The tungsten being deposited on to the filament, and the halogen released to repeat the cycle.



The filament temperature of tungsten halogen tubes is around 2700 °C, equivalent to a peak wavelength of 1 micron. The color temperature is therefore similar to an incandescent lamp bulb. Ratings up to 20 kW per tube are available, with a heated length up to 670 mm.

The main applications for this concentrated high intensity heat source are in the research field for materials testing.