Chapter 2

Basics of Noncontact Thermal Measurements

2.1 Heat Transfer and Radiation Exchange Basics

This section will provide the reader with an understanding of how heat transfer phenomena affect noncontact IR thermal sensing and thermographic measurements. Since making IR measurements depends on measuring the distribution of radiant thermal energy (heat) emitted from a target surface, the *thermographer* must have a sound understanding of heat, temperature and the various types of heat transfer to undertake an effective program of IR thermal imaging, or *thermography*.

2.1.1 Heat and temperature

What we often refer to as a heat source (like an oil furnace or an electric heater) is really one form or another of energy conversion; the energy stored in one object is converted to heat and flows to another object. *Heat* can be defined as *thermal energy in transition*. It flows from one place or object to another as a result of temperature difference, and the flow of heat changes the energy levels in the objects. *Temperature* is a property of matter and not a measurement of internal energy. It defines the direction of heat flow when another temperature is known.

Heat always flows from the object that is at the higher temperature to the object that is at the lower temperature.

As a result of heat transfer, hotter objects tend to become cooler and cooler objects become hotter, approaching thermal equilibrium. To maintain a steady-state condition, energy needs to be continuously supplied to the hotter object by some means of energy conversion so that the temperatures, and hence the heat flow, remain constant.

2.1.2 Converting temperature units

Temperature is expressed in either absolute or relative terms. There are two absolute scales called *Rankine* (English system) and *Kelvin* (metric system). There are two corresponding relative scales called *Fahrenheit* (English system) and *Celsius* or *centigrade* (metric system).

Absolute zero is the temperature at which no molecular action takes place. This is expressed as zero Kelvins or zero Rankines (0 K or 0 R). Relative temperature is expressed as degrees Celsius or degrees Fahrenheit (°C or °F). The numerical relations among the four scales are as follows:

$$T_{Celsius} = \frac{T_{Fahrenheit} - 32}{1.8}, \tag{2.1}$$

$$T_{Fahrenheit} = 1.8\ (T_{Celsius} + 32), \tag{2.2}$$

$$T_{Rankine} = T_{Fahrenheit} + 459.69, \tag{2.3}$$

$$T_{Kelvin} = T_{Celsius} + 273.16. \tag{2.4}$$

Absolute zero is equal to –273.1°C and to –459.7°F. To convert *changes in temperature* or *delta T* (ΔT) between the English and metric systems, the simple 9/5 (1.8 to 1) relationship is used:

A ΔT of 1°Celsius is equal to a ΔT of 1.8°Fahrenheit. (2.5)

Table 2.1, located at the end of this chapter, is a conversion table to allow the rapid conversion of temperature between Fahrenheit and Celsius values. The table includes instructions for its use.

2.1.3 Three modes of heat transfer

There are three modes of heat transfer: *conduction*, *convection,* and *radiation*. All heat transfer processes occur by one or more of these three modes. Infrared thermography is based on the measurement of radiative heat flow and is therefore most closely related to the radiation mode of heat transfer.

2.1.4 Conduction

Conduction is the transfer of heat in stationary media. It is the only mode of heat flow in solids but can also take place in liquids and gases. It occurs as the result of molecular collisions (in liquids) and atomic vibrations (in solids) whereby energy is moved, one molecule at a time, from higher temperature sites to lower temperature sites. Figure 2.1 is an illustration of conductive heat flow.

The Fourier conduction law expresses the conductive heat flow through the slab shown in Fig. 2.1,

$$\frac{Q}{A} = \frac{k(T1 - T2)}{L}, \tag{2.6}$$

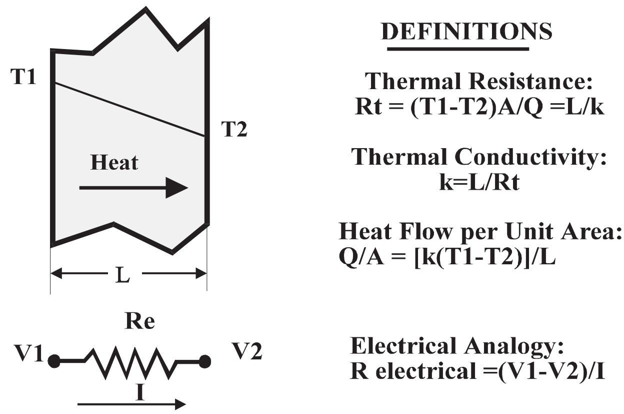


Figure 2.1 Conductive heat flow.

where Q/A is the rate of heat transfer through the slab per unit area (BTU/h-ft^2) perpendicular to the flow, L is the thickness of the slab (ft), T1 (deg F) is the higher temperature (at the left), T2 is the lower temperature (at the right), and k is the thermal conductivity of the slab material. Thermal conductivity is analogous to electrical conductivity and inversely proportional to thermal resistance, as shown in the lower portion of Fig. 2.1. The temperatures T1 and T2 are analogous to voltages V1 and V2, and the heat flow Q/A is analogous to electrical current I, so that if

$$\text{R electrical} = \frac{\text{V1} - \text{V2}}{\text{I}}, \tag{2.7}$$

then

$$\text{R thermal} = \frac{\text{T1} - \text{T2}}{\text{Q/A}} = \frac{\text{L}}{\text{k}}. \tag{2.8}$$

Heat flow is usually expressed in English units, where k is expressed in BTU/hr-ft^2-°F and thermal resistance is in °F-hr-ft^2/BTU.

2.1.5 Convection

Convective heat transfer takes place in a moving medium and is almost always associated with transfer between a solid and a moving fluid (such as air). Forced convection takes place when an external driving force, such as a wind or an air pump, moves the fluid. Free convection takes place when the temperature differences necessary for heat transfer produce density changes in the fluid and the warmer fluid rises as a result of increased buoyancy.

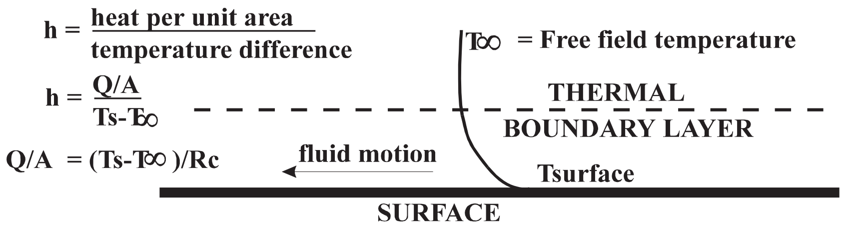


Figure 2.2 Convective heat flow.

In convective heat flow, heat transfer takes effect by means of two mechanisms; the direct conduction through the fluid, and the motion of the fluid itself. Figure 2.2 illustrates convective heat transfer between a flat plate and a moving fluid.

The presence of the plate causes the velocity of the fluid to decrease to zero at the surface and influences its velocity throughout the thickness of a *boundary layer*. The thickness of the boundary layer depends on the free velocity, V, of the fluid. It is greater for free convection and smaller for forced convection. The rate of heat flow depends in turn on the thickness of the convection layer as well as the temperature difference between T_s and T_∞ (T_s is the surface temperature, T_∞ is the free field fluid temperature outside the boundary layer). Newton's cooling law defines the convective heat transfer coefficient as

$$h = \frac{Q/A}{T_s - T_\infty}, \tag{2.9}$$

where h is expressed in BTU/hr-ft^2-°F.

By rearranging Eq. (2.9), we obtain

$$\frac{Q}{A} = T_s - \frac{T}{R_c}, \tag{2.10}$$

where R_c =1/h is the resistance to convective heat flow. Rc is also analogous to electrical resistance and is easier to use when determining combined conductive and convective heat transfer.

2.1.6 Radiation

Radiative heat transfer is unlike the other two modes in several respects:

1. It can take place across a vacuum.
2. It occurs by electromagnetic emission and absorption.
3. It occurs at the speed of light.
4. The energy transferred is proportional to the fourth power of the temperature difference between the objects.

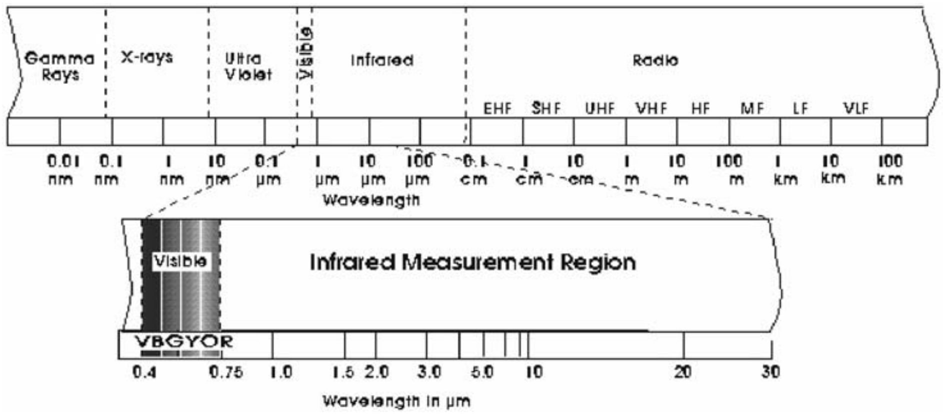
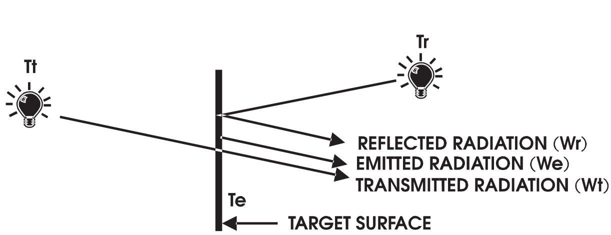


Figure 2.3 Infrared in the electromagnetic spectrum.

The electromagnetic spectrum is illustrated in Fig. 2.3. Radiative heat transfer takes place in the IR portion of the spectrum, from 0.75 µm to about 100 µm, although most practical measurements can be made out to about 20 µm (µ or µm stands for micrometers or *microns*. A micron is one-millionth of a meter and the measurement unit for radiant energy wavelength).

2.1.7 Radiation exchange at the target surface

The measurement of thermal IR radiation is the basis for noncontact temperature measurement and thermography. Thermal IR radiation leaving a surface (W) is called *exitance* or *radiosity*. It can be emitted from the surface, reflected off the surface, or transmitted through the surface. This is illustrated in Fig. 2.4. The total radiosity is equal to the sum of the emitted component (We), the reflected component (Wr) and the transmitted component (Wt). *The surface temperature is related to* We, *the emitted component, only.*



%We + %Wr + %Wt = 100%

$$We = \sigma\varepsilon Te^4$$
$$Wr \propto \sigma\varepsilon Tr^4$$
$$Wt \propto \sigma\varepsilon Tt^4$$

We + Wr + Wt = Target Exitance or Radiosity

Figure 2.4 Radiative heat flow.

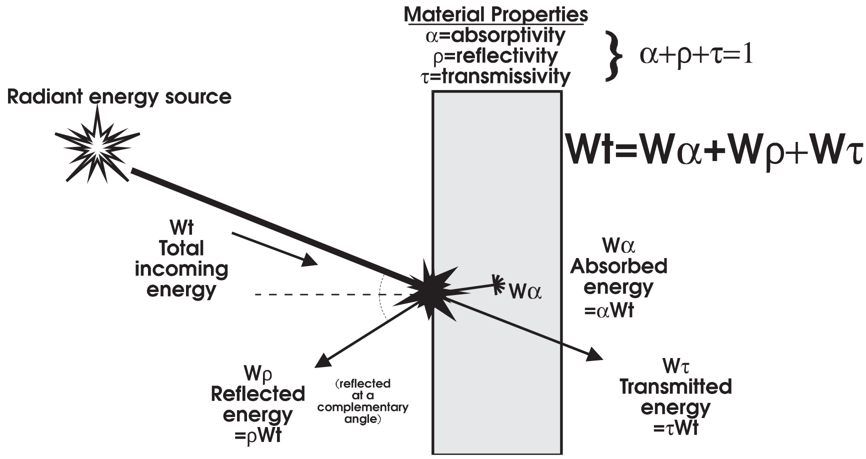


Figure 2.5 Radiation impinging on a surface.

Thermal IR radiation impinging on a surface can be absorbed, reflected, or transmitted as illustrated in Fig. 2.5. Kirchhoff's law states that the sum of the three components is always equal to the received radiation (the percentage sum of the three components equals unity):

$$\alpha \text{ (absorptivity)} + \rho \text{ (reflectivity)} + \tau \text{ (transmissivity)} = 1.$$

2.1.8 Specular and diffuse surfaces

The roughness and surface characteristics will determine the type and direction of reflection of incident radiation. A smooth surface will reflect incident energy at an angle complementary to the angle of incidence. This is called a *specular* reflector. A rough or structured surface will scatter or disperse some of the incident radiation. This is called a *diffuse* reflector. No perfectly specular or perfectly diffuse surface can exist in nature. All real surfaces have some diffusivity and some specularity.

When making practical measurements, the specular or diffusing characteristics of a target surface are taken into effect by accounting for the emissivity of the surface. Emissivity is discussed as part of the detailed discussion of the characteristics of IR thermal radiation in Sec. 2.3.

2.1.9 Transient heat exchange

The discussions of three types of heat exchange in Secs. 2.1.4–2.1.6 deal with *steady-state* heat exchange for reasons of simplicity and ease of understanding. Two fixed temperatures are assumed to exist at the two points between which the heat flows. In many applications, however, temperatures are in transition, so that the values shown for energy radiated from a target surface are the *instantaneous* values at the moment measurements are made. There are numerous instances where existing transient thermal conditions are exploited in order to use thermography to reveal material or structural characteristics in test articles. The thermogram of the outside surface of an insulated vessel carrying heated liquid, for example, should be relatively isothermal and somewhat warmer than the ambient air. Insulation voids or defects will cause warm anomalies to appear on the thermogram, allowing the thermographer to pinpoint areas of defective or damaged insulation. Here a passive approach can be taken because the transient heat flow from the liquid through the insulation to the outside air produces a characteristic thermal pattern on the product surface. Similarly, water-saturated areas on flat roofs will retain solar heat well into the night. Long after the dry sections have radiated their stored heat to the cold night sky, the saturated sections will continue to radiate, and will appear as warm anomalies to the thermographer.

When there is no heat flow through the material or the test article to be evaluated, an active, or *thermal injection*, approach is used to generate a transient heat flow. This approach requires: (1) the generation of a controlled flow of thermal energy across the laminar structure of the sample material under test; (2) thermographic monitoring of one of the surfaces (or sometimes both) of the sample; and (3) the search for the anomalies in the thermal patterns so produced that will indicate a "defect" in accordance with established accept-reject criteria. This approach has been used extensively and successfully by the aerospace community in the evaluation of composite structures for impurities, flaws, voids, disbonds, delaminations, and variations in structural integrity. A more detailed discussion of thermal IR nondestructive material testing is provided in Chapter 9.

2.2 Infrared Measurement Problem

All targets radiate energy in the IR spectrum, as shown in Fig. 2.7. The hotter the target, the more energy is radiated. Very hot targets radiate in the visible as well, and our eyes can see this because they are sensitive to light. For example, the sun at about 6000 K appears to glow almost white hot, a tungsten filament at about 3000 K has a yellowish glow, and an electric stove element at 800 K glows red. As the stove element cools it loses its visible glow but it continues to radiate. We can feel it with a hand placed near the surface but we can't see the glow because the energy has shifted from red to IR. Infrared detectors can sense IR radiant energy and produce useful electrical signals proportional to the temperature of target surfaces. Instruments using IR detectors and optics to gather and focus energy from the targets onto these detectors are capable of measuring target surface *spot* temperatures with sensitivities down to 0.1°C and with response times in the microsecond range. They are called *point sensors* or *spot radiometers*. Instruments that combine this measurement capability with mechanisms for scanning the target surface are called *infrared thermal imagers* or *infrared cameras*. They can produce thermal maps or *thermograms* where the brightness intensity or color hue of any spot on the map is representative of the temperature of the surface at that point.

In most cases, thermal imagers can be considered as extensions of radiation thermometers or as arrays of radiation thermometers operating simultaneously. The performance parameters of thermal imagers are extensions of the performance parameters of radiation thermometers. For ease of understanding, therefore, the basic measurement problem is discussed in this chapter in terms of the measurement of a single point. It is then expanded to cover thermal scanning and imaging.

2.2.1 Noncontact thermal measurements

Infrared noncontact thermal sensors are classified as *infrared radiation thermometers* by the American Society for Test and Measurement (ASTM) even though they don't always read out in temperature. The laws of physics allow us to convert IR radiation measurements to temperature measurements. We do this by measuring the self-emitted radiation in the IR portion of the electromagnetic spectrum from target surfaces and converting these measurements to electrical signals. In making these measurements three sets of characteristics need to be considered, as illustrated in Fig. 2.6:

- The target surface.
- The transmitting medium between the target and the instrument.
- The measuring instrument.

2.2.2 Target surface

The chart of the electromagnetic spectrum (Fig. 2.3) indicates that the IR portion of the spectrum lies adjacent to the visible. Every target surface above absolute zero (0 K or –273°C) radiates energy in the IR. The hotter the target, the more radiant energy is emitted. When targets are hot enough they radiate or "glow" in the visible part of the spectrum as well. As they cool, our eyes become incapable of seeing their emitted radiation and they appear not to glow at all. Infrared sensors are employed here to measure the radiation in the IR, which is related to target surface temperature.

The visible spectrum extends from energy wavelengths of 0.4 μm for violet light to about 0.75 μm for red light. The IR spectrum extends from 0.75 μm to about 20 μm for practical purposes of temperature measurement.

Figure 2.7 shows the distribution of emitted energy over the electromagnetic spectrum of targets at various temperatures. The sun, at 6000 K, appears almost white hot since its emitted energy is centered over the visible spectrum with a peak at 0.5 μm. Other targets, such as a tungsten filament at 3000 K, a red hot surface at 800 K, and the ambient earth at 300 K (about 30°C) are also shown in this illustration. It becomes apparent that, as surfaces cool, not only do they emit less energy, but the wavelength distribution shifts to longer IR wavelengths. Even though the eye becomes incapable of sensing this energy, IR sensors can "see" these invisible longer wavelengths. They enable us to measure the self-emitted radiant energy from even very cold targets and, thereby, determine the temperatures of target surfaces remotely and without contact.

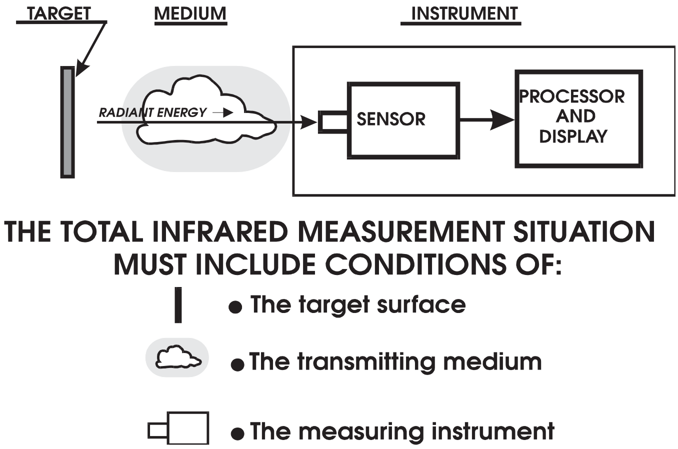


Figure 2.6 Three sets of characteristics in making IR measurements.

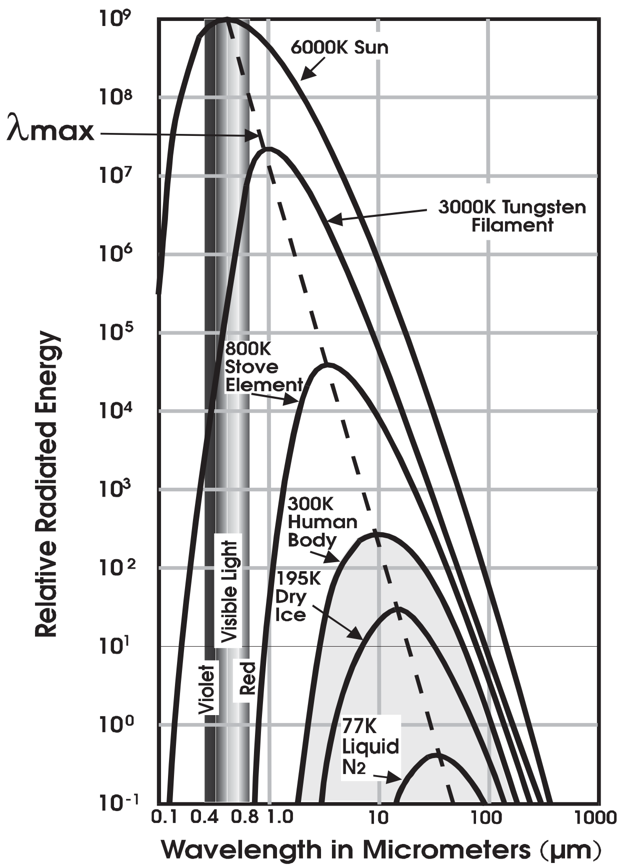


Figure 2.7 Blackbody curves at various temperatures.