Module 4.2

Radiation properties of surfaces

Introduction:

Radiation properties of surfaces are important in many engineering applications. For example, the heat loss from a heated object such as an electronic component fixed on a printed circuit board depends on the surface emissivity of the electronic component. In recent times these also are important in computer graphics where realistic shadowing and shading patterns are based on the realistic simulation of surface properties such as the reflectance pattern of the surface due to directional illumination of the surface

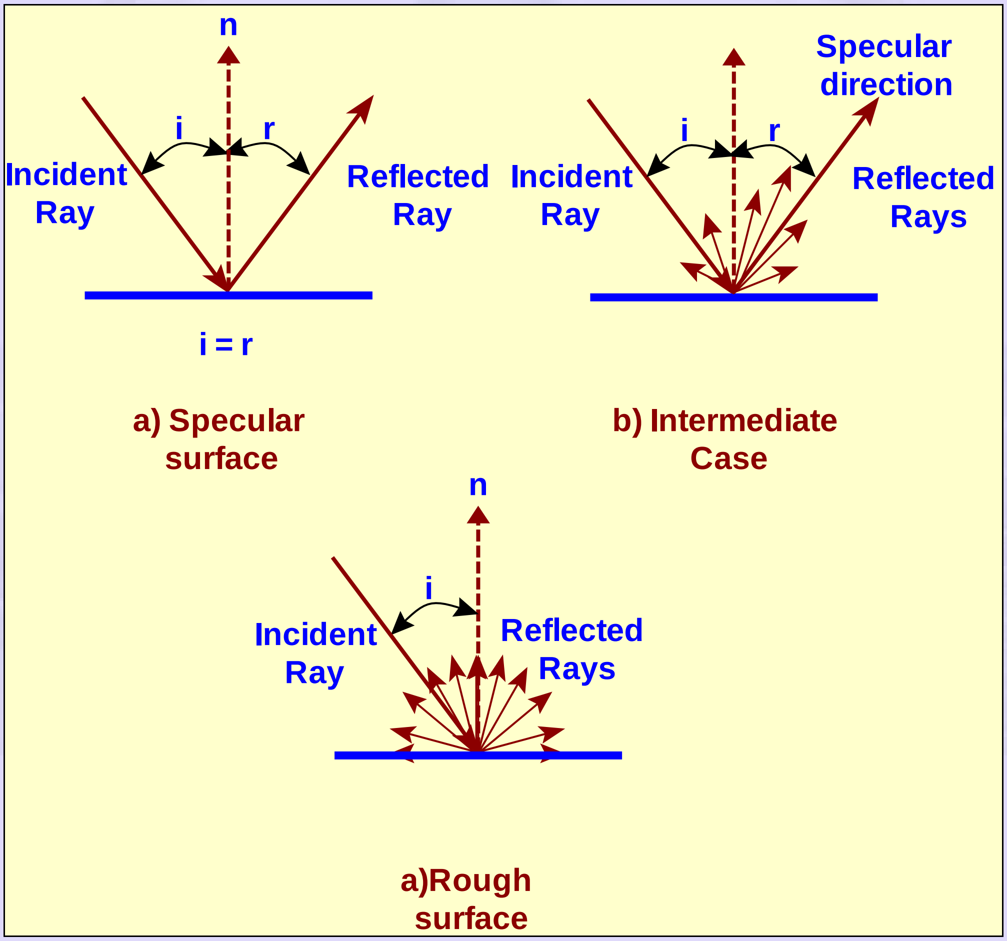

Figure 22 Schematic representation of reflection at an opaque surface

We restrict our discussion below to a surface that is opaque and hence radiation is either reflected or absorbed at the surface. Consider first an optically smooth flat surface. The surface roughness as a fraction of the wavelength of radiation should be small, say 0.1, for a surface to be considered optically smooth. Such a surface reflects radiation specularly following the laws of geometric optics. The incident ray, the reflected ray and the normal to the surface, at the point of incidence are all in the same plane. Also the angle made by the incident ray with the surface normal is equal to the angle made by the reflected ray with the surface normal (see Figure 22a). Engineering surfaces are seldom smooth, and, in the extreme, may be considered perfectly rough (Figure 22c). Many reflected rays are produced going into all the directions of a hemisphere that may be constructed at the point of incidence. The reflection is direction independent and we refer to the surface as being perfectly diffuse or simply diffuse. Real surfaces, however, may have reflectance behavior in between the specular and diffuse extremes as shown schematically by Figure 22b. This case exhibits the most complex measurement situation. The reflectance may be some what larger along the specular direction compared to all other directions represented by the hemisphere centered at the point of incidence.

Definitions:

We have already discussed some aspects of radiation while dealing with pyrometry. Here we consider those aspects that are relevant from the point of view of surface properties. We may consider either spectral or total quantities depending on the nature of the measurement that is being made.

Consider a surface that is maintained at a constant temperature of T_s. Let the spectral emissive power of this surface be $E_\lambda(T_s)$. A black body at the same temperature would have a spectral emissive power given by $E_{b\lambda}(T_s)$. This is described by the familiar Planck distribution function. The spectral hemispherical emissivity (or simply the spectral emissivity) $_{,h}$ of the surface is defined as

$$\varepsilon_{\lambda,h} = \frac{E_\lambda(T_s)}{E_{b\lambda}(T_s)} \qquad \textbf{(20)}$$

The corresponding total quantity is obtained by integrating with respect to the wavelength. Equation 20 will then be replaced by

$$\varepsilon_h = \frac{E(T_s)}{E_b(T_s)} = \frac{\int_0^\infty E_\lambda(T_s)\,d\lambda}{\int_0^\infty E_\lambda(T_s)\,d\lambda} = \frac{\int_0^\infty E_\lambda(T_s)\,d\lambda}{\sigma T_s^4} \qquad \textbf{(21)}$$

Angular quantities (angle dependent surface properties) are defined now. Consider radiation incident within a cone defined by the incident direction θ,ϕ as shown in Figure 23. Radiation reflected in a direction defined by θ',ϕ' is indicated by the reflected cone in the figure. The incident radiation is characterized by the incident intensity $I_\lambda(\theta,\phi)$ while the reflected intensity is characterized by $I_\lambda(\theta',\phi')$. Ratio of the reflected intensity to the incident intensity is thus a function of (θ,ϕ) and (θ',ϕ') and represents the so called bidirectional reflectivity $\rho_\lambda(\theta,\phi;\theta',\phi')$ of the surface.

Our interest here is only with the hemispherical quantities. For this we consider two cases.

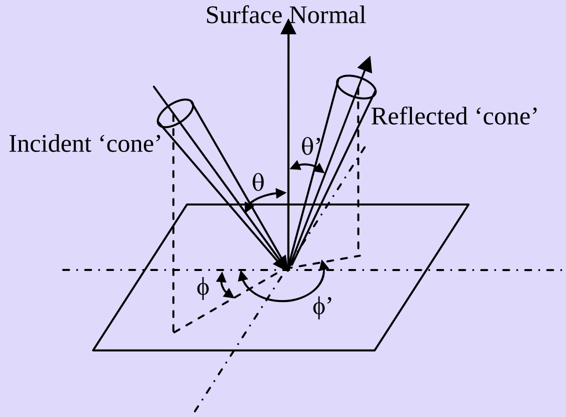

Figure 23 Biangular reflection at a surface

Directional hemispherical reflectivity

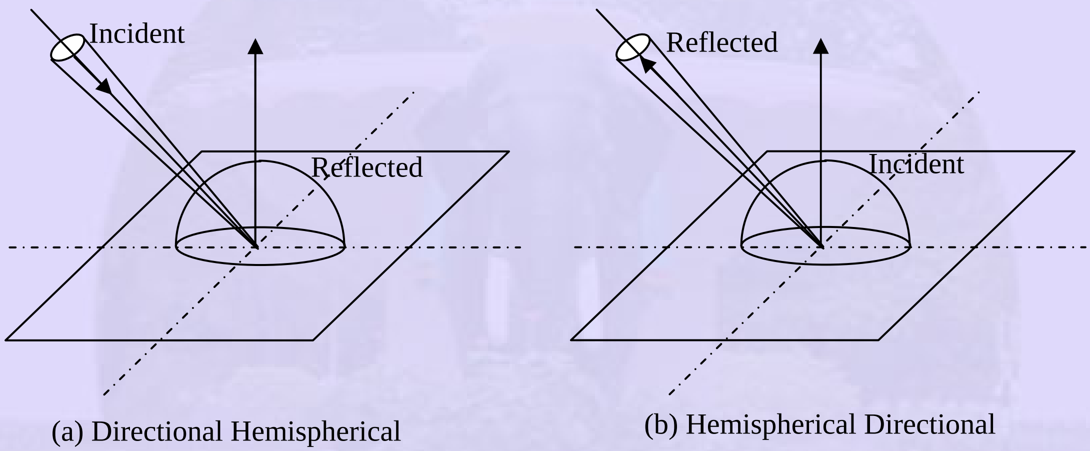

Figure 24 Directional hemispherical and hemispherical directional reflectivities

Consider radiation incident along θ,ϕ direction and that reflected along all the directions of the hemisphere as shown in Figure 24 (a). The incident radiant flux is given by $I_\lambda(\theta,\phi)\cos\theta d\Omega$ where dΩ represents the elemental solid angle represented by the incident cone. The hemispherical reflected flux is given by $\int\limits_{\Omega'=2\pi} I_\lambda(\theta',\phi')\cos\theta' d\Omega'$. The integration is over the hemisphere represented by the total solid angle of 2π. We may rewrite the reflected flux as

$$\int_{\Omega'=2\pi} I_\lambda(\theta,\phi)\rho_\lambda(\theta,\phi;\theta',\phi')\cos\theta' d\Omega'$$

where $\rho_\lambda(\theta,\phi;\theta',\phi')$ is the bidirectional reflectivity. Noting that $I_\lambda(\theta,\phi)$ is constant since the incident direction is fixed, this may be taken outside the integral sign. The directional hemispherical reflectivity is then given by

$$\rho_{\lambda,h}(\theta,\phi) = \frac{\int_{\Omega'=2\pi} \rho_\lambda(\theta,\phi;\theta',\phi')\cos\theta' d\Omega'}{\cos\theta d\Omega} \quad \textbf{(22)}$$

If the incident radiation is coming in through the entire hemisphere we may define the hemispherical reflectivity of the surface as

$$\rho_{\lambda,h} = \frac{\int_{\Omega=2\pi} \rho_{\lambda,h}(\theta,\phi) I_\lambda(\theta,\phi)\cos\theta d\Omega}{\int_{\Omega=2\pi} I_\lambda(\theta,\phi)\cos\theta d\Omega} \quad \textbf{(23)}$$

In engineering applications our interest is mostly with diffuse incident radiation that is characterized by an angle independent or isotropic intensity. In such a case $I_\lambda(\theta,\phi) = I_\lambda$ and may be removed out of the integral sign in Equation 24. Also note that $d\Omega = \sin\theta d\theta d\phi$. If in addition, we assume that reflection is independent of ϕ the integral in the denominator becomes

$$\int_{\Omega=2\pi} I_\lambda(\theta,\phi)\cos\theta d\Omega = I_\lambda \int_0^{\frac{\pi}{2}}\int_0^{2\pi} \cos\theta\sin\theta d\theta d\phi = 2\pi I_\lambda \int_0^{\pi/2} \sin\theta\cos\theta d\theta = \pi I_\lambda \quad \textbf{(24)}$$

Equation 24 then takes the form

$$\rho_{\lambda,h} = \frac{1}{\pi}\int_\Omega \rho_{\lambda,h}(\theta,\phi)\cos\theta d\Omega \quad \textbf{(25)}$$

If the surface is opaque (most engineering applications deal with opaque surfaces) the hemispherical reflectivity is given by

$$\rho_{\lambda,h} = 1 - \alpha_{\lambda,h} \quad \textbf{(26)}$$

where α is the absorptivity of the surface.

Hemispherical directional reflectivity

Let the incident radiation come from all the directions of the hemisphere as shown in Figure 24 (b). The incident flux is then given by $\int_{\Omega=2\pi} I_\lambda(\theta,\phi)\cos\theta d\Omega$. The hemispherical directional reflectivity is then given by

$$\rho_{\lambda,h}(\theta',\phi') = \frac{\int_\Omega \rho_\lambda(\theta,\phi;\theta',\phi') I_\lambda(\theta,\phi)\cos\theta d\Omega}{\int_\Omega I_\lambda(\theta,\phi)\cos\theta d\Omega} \qquad (27)$$

The reflected direction represented by θ',ϕ' remains fixed in the above expression.

Complicating features:

Radiation measurements are, in general, expensive because of high quality instruments that are needed. The measurement of spectral properties (pertaining to different incident light frequency or wavelength) requires expensive monochromator. Suitable sources of radiation and detectors are required (for covering the ultraviolet, visible and infrared radiation). Total reflectance (integrated over all frequencies of incident radiation) is normally easier to measure and less expensive. If a surface is perfectly rough there is no angular variation of reflectivity and hence easy to measure. In what follows we shall look into the details of each of these.

Components of a reflectivity measuring instrument:

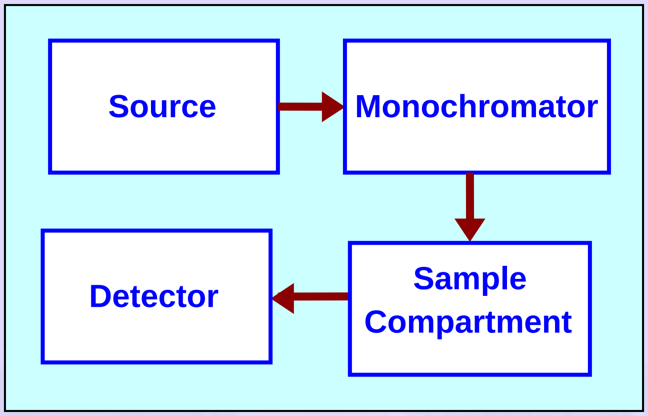

Figure 23 Schematic of a radiation measuring instrument

The components of a radiation measuring instrument are shown schematically in Figure 23. The instrument may either be a single or double beam instrument depending on the requirement. The source of radiation is appropriately chosen with the requirement of the instrument in mind. Special lamps are used for measurement in the ultraviolet part of the spectrum. The visible part of the spectrum is covered by the use of filament type source. To cover the infrared part of the spectrum the source is usually a glower that consists of an electrically conducting element in the form of a long cylinder. A DC current is directly passed through the element to run it at a temperature of around 1000 K. The glower is cooled with circulating water at the two ends. The light from the source is collimated and is passed through a slit before it is passed on to the monochromator.

Monochromator is a device that selects a single wavelength to emerge out of it before it is incident on the test surface. It may use a prism (Figurer 24), grating

(Figure 25) or an interferometer (Figure 26). In the last case the spectrum is obtained by suitable processing of the signal by converting the time domain signal to frequency domain.

The sample compartment allows the incident light to be incident on the surface of the specimen at the desired incident angle. It also has a suitable arrangement by which the reflected radiation in a particular direction or in all the directions of the hemisphere is collected and passed on to the detector. The last action is possible by the use of an integrating sphere that will be discussed later on.

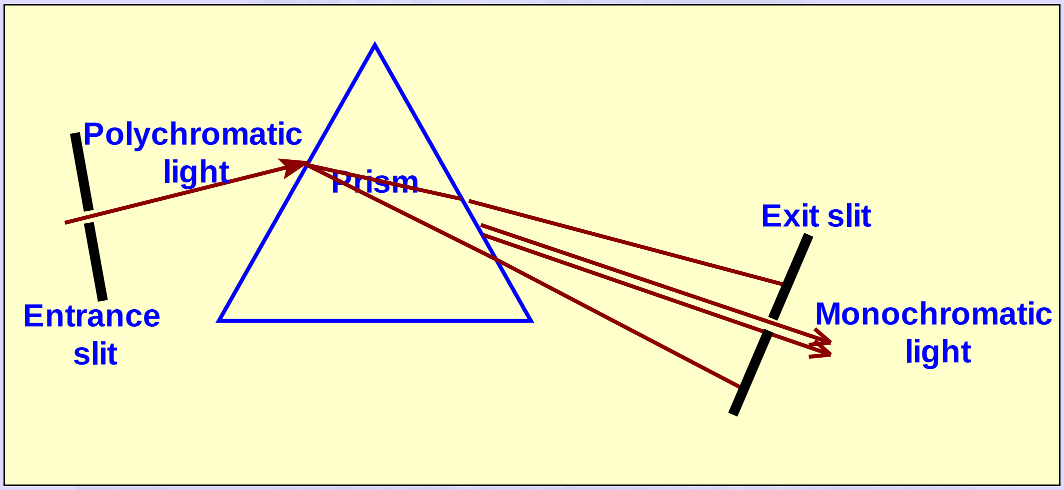

Figure 24 Schematic of a Prism Monochromator

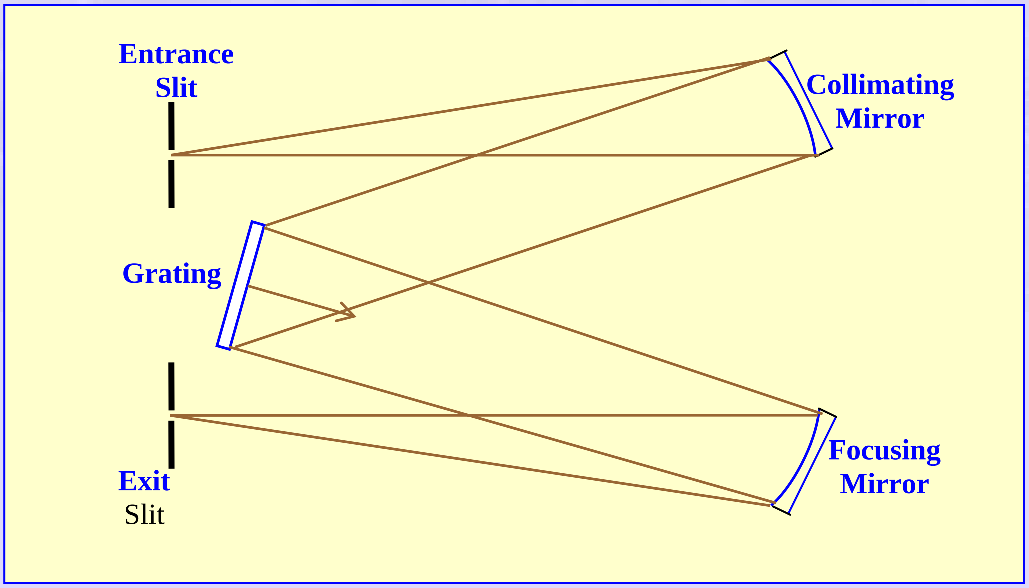

Figure 25 Schematic of a Grating Monochromator

The detector may consist of a broad band thermal detector (a thermopile), photo-conducting detector (infrared) or a photo-multiplier tube as in the case of detection of visible radiation.

Suitable optical elements like mirrors, lenses, and beam splitters are required in the instrument (as is evident from Figures 24-26). Also required will be suitable electronics for detection and processing of the data. Most modern instruments are connected, to a computer with suitable digital processing cards, for this purpose.

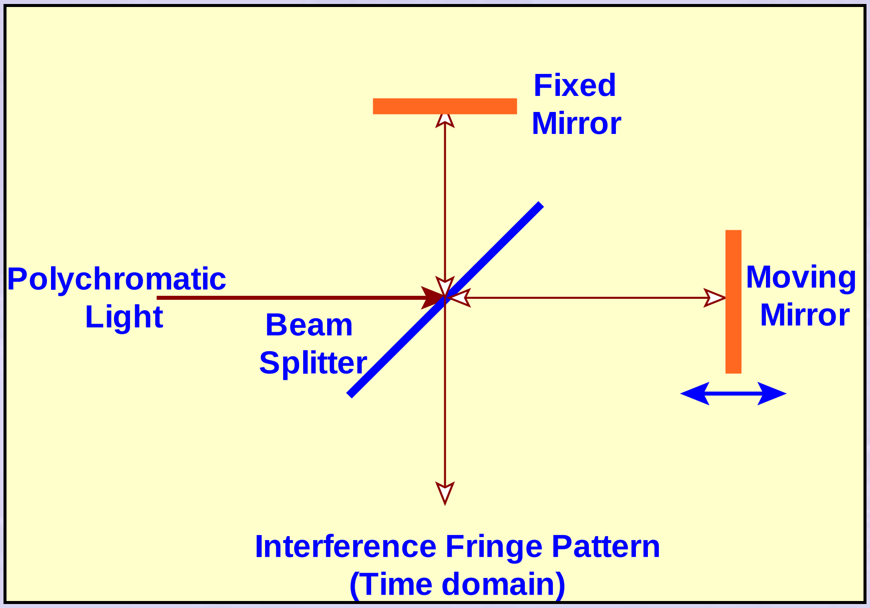

Figure 26 Schematic of a Fourier Transform Infrared Spectrometer

Integrating sphere and the measurement of hemispherical directional reflectivity or directional hemispherical reflectivity

We describe the use of an integrating sphere for the purpose of measuring hemispherical properties of a surface. An integrating sphere consists of a spherical shell, usually made of aluminum, with the inside surface coated with a highly reflecting diffuse coating (typically magnesium oxide or proprietary paints). Suitable ports are provided for allowing light to enter and leave the integrating sphere. Arrangement is also made for placing a test surface within the sphere. The integrating sphere may have a diameter of a few centimeters to as much as a meter.

Figure 27 Photograph of an integrating sphere

Figure 27 shows the external appearance of an integrating sphere. Typical reflectivity of the coating used in the integrating sphere is shown in Figure 28. The working principle of the integrating sphere is explained by taking the case of measurement of hemispherical properties as examples.

Hemispherical directional reflectivity

Hemispherical directional reflectivity means the reflectivity along a particular direction when the radiation is incident on the test surface from all directions represented by a hemisphere. The integrating sphere makes it possible to *illuminate* the test surface from all directions represented by a hemisphere.

The arrangement shown in Figure 29 is suitable for measuring the hemispherical directional reflectivity of a test surface. Collimated light is incident on to some location on the integrating sphere through an entrance port. Since the integrating sphere is highly reflecting and diffuse this light is sent in to all the directions of a hemisphere. Any ray among these reaches the test surface placed at a location elsewhere on the sphere either directly after just a single reflection or after a number of reflections off the surface of the integrating sphere. Hence it is clear that the test surface is *illuminated* by isotropic radiation intensity. The light reflected off the test surface may be sampled along the desired direction as shown in the figure.

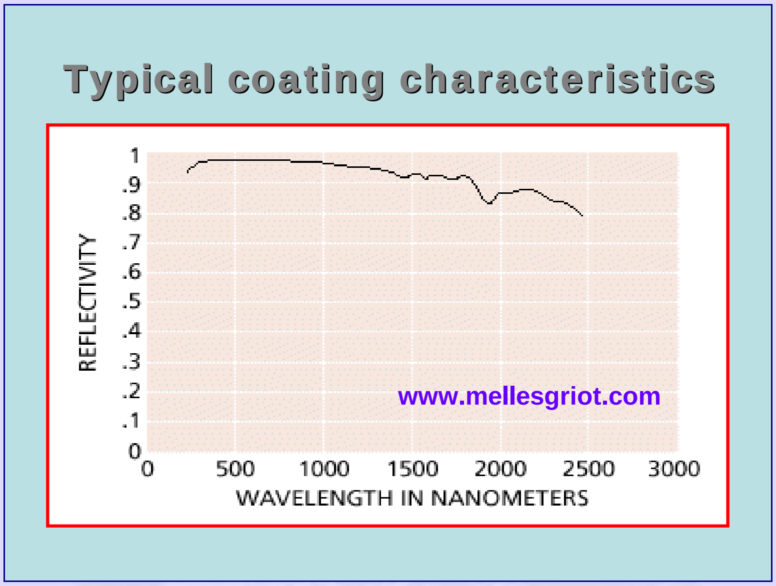

Figure 28 Reflectivity of typical coating used in the integrating sphere

A light detector placed anywhere on the sphere will indicate a signal proportional to the flux incident on the test surface. The light reflected is also measured using a detector to yield a signal proportional to the reflected intensity. Ratio of the latter signal and the former will yield the hemispherical directional reflectivity of the test surface. If the incident radiation is taken from a monochromator the measurement yields spectral reflectivity. If the incident radiation is from a black body the reflectivity will be the total reflectivity.

Directional hemispherical reflectivity

Directional hemispherical reflectivity means the reflectivity of the test surface in to all directions represented by a hemisphere of radiation incident along a given direction. The integrating sphere makes it possible to *collect* the radiation leaving the test surface along all directions represented by a hemisphere.

In this case the test surface is mounted on a suitable platform that may be oriented such that it is illuminated by collimated radiation along a desired direction. The reflected radiation leaving the test surface along all the directions of the hemisphere is collected by the integrating sphere and is incident on a detector placed elsewhere on its surface, as shown in Figure 30. The incident flux is measured independently by a second detector. This may be done, as for example, by dividing the incoming radiation in to two parts by using a beam splitter, and placing the detector to measure the beam reflected off the beam splitter. The beam that is transmitted by the beam splitter is incident on the test surface and represents a known fraction of the original beam. The reflectivity of the test surface is again estimated based on the ratio of two signals.

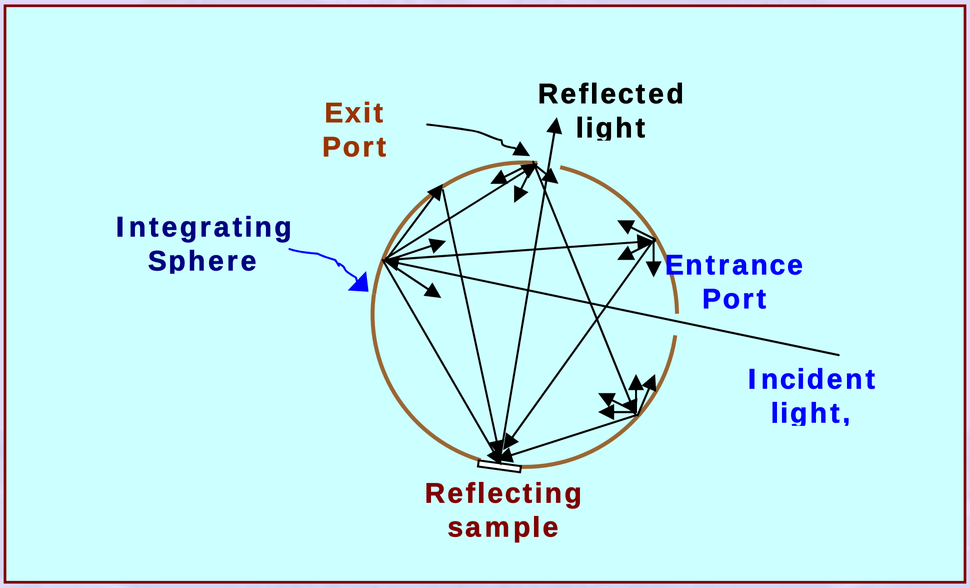

Figure 29 Integrating sphere arranged for measurement of hemispherical directional reflectivity

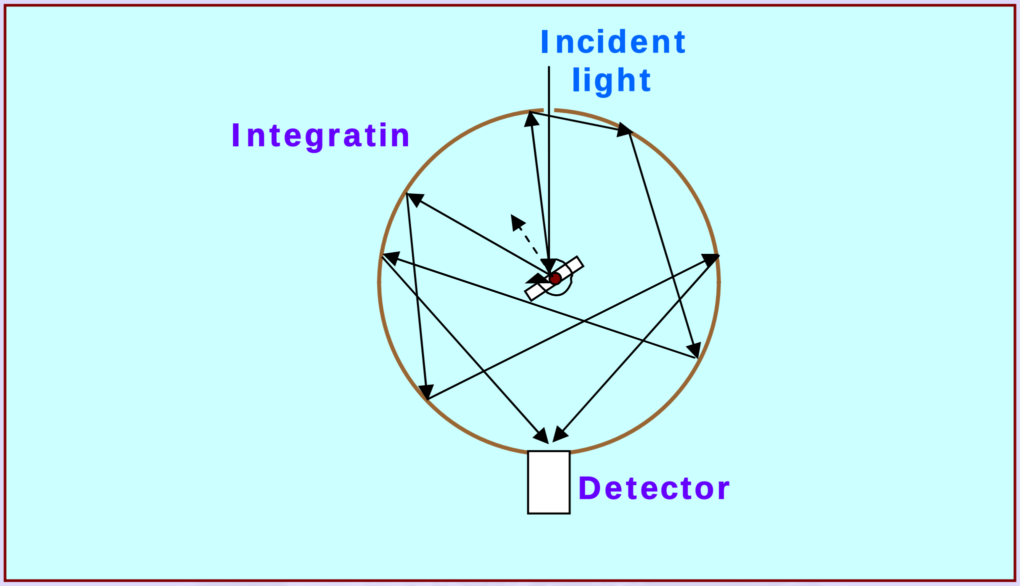

Figure 30 Integrating sphere arranged for measurement of directional hemispherical reflectivity

Emissivity measurement:

An alternate method of studying radiation surface property is to measure the surface emissivity, either the total/spectral hemispherical emissivity or the corresponding directional values. In most thermal applications of radiation the hemispherical emissivity is adequate to describe the thermal process. The test surface is maintained at an elevated temperature by heating it so that it emits radiation. Measurement of this radiation and comparison with that from a black body at the same temperature yields the emissivity of the test surface. However, many of the components that are present in the reflectivity measurement are also present in this case.

There are several methods available for the measurement of emissivity. We consider a few of them here.

a) Emissivity measurement using an integrating radiometer

The integrating radiometer consists of a hemisphere at the middle of which the heated test surface and a thermopile detector are kept at small but equal distances off center as shown in Figure 31. The inside surface of the hemisphere is highly polished aluminum which acts as a highly reflecting specular surface. Any ray of radiation that leaves the test surface (one such is shown in the figure) is reflected specularly and is incident on the thermopile. The integrating sphere (actually the hemisphere) thus brings all the rays that leave the test surface to incident on the thermopile. Hence the hemispherical emissivity of the surface is obtained by comparing the signal registered by the thermopile with the test surface against a black body at the same temperature. The sphere itself needs to be water cooled such that the sphere is at room temperature while the test surface is maintained at an elevated temperature. Otherwise emission from the sphere will contribute to error in the measurement.

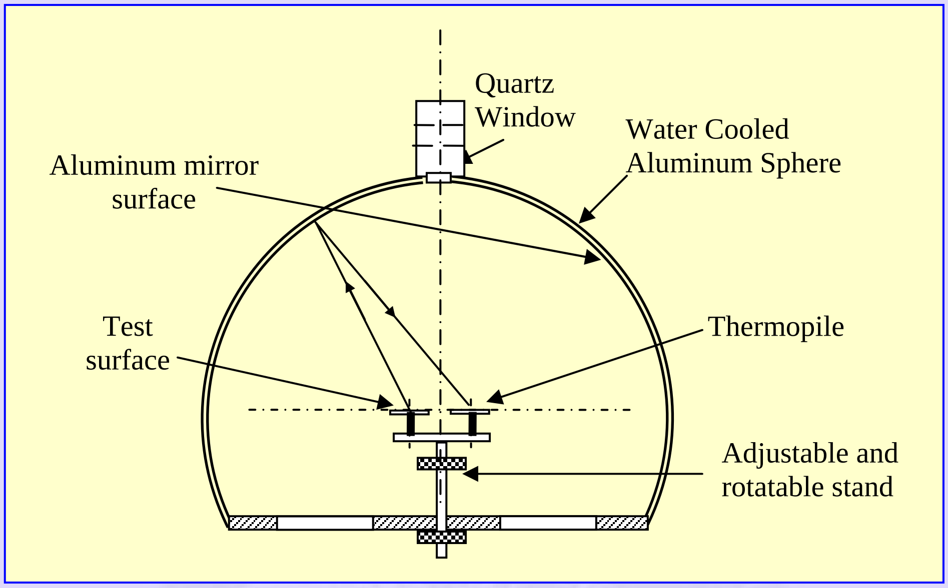

Figure 31 Integrating radiometer

b) Emissivity by transient cooling in vacuum

A second method of emissivity of a surface is by performing a cooling experiment. The test surface is taken in the form of a thin plate with a substrate of high thermal conductivity. The test plate is suspended by thin supporting wires inside a large vacuum environment. The walls of the vacuum chamber are cooled by a suitable arrangement and maintained at a low temperature. The test plate is heated to an elevated temperature and allowed to cool starting at t = 0. If all other modes of heat transfer are negligible in comparison with surface radiation, the cooling of the plate is governed by the equation

$$Mc\frac{dT}{dt} = -\varepsilon_h \sigma \left(T^4 - T_{bkg}^4\right) \quad \textbf{(28)}$$

It is assumed that the heated plate behaves as a lumped system. In Equation 28 M represents the mass of the plate, c the specific heat of the plate material, T_{bkg} the constant background temperature provided by the walls of the vacuum chamber and σ is the Stefan-Boltzmann constant..

The cooling rate and hence the cooling history of the plate is a function of hemispherical emissivity ε_h. Typically the temperature history as a function of ε_h is as shown in Figure 32. This figure is based on a simulation where ε_h is assumed known, along with all the other parameters that occur in Equation (28). In practice the temperature time history is recorded by a data logger. The background temperature is measured independently. The mass of the plate is determined by using a precision balance and the specific heat may be either measured by an independent experiment or obtained from manufacturer provided data.

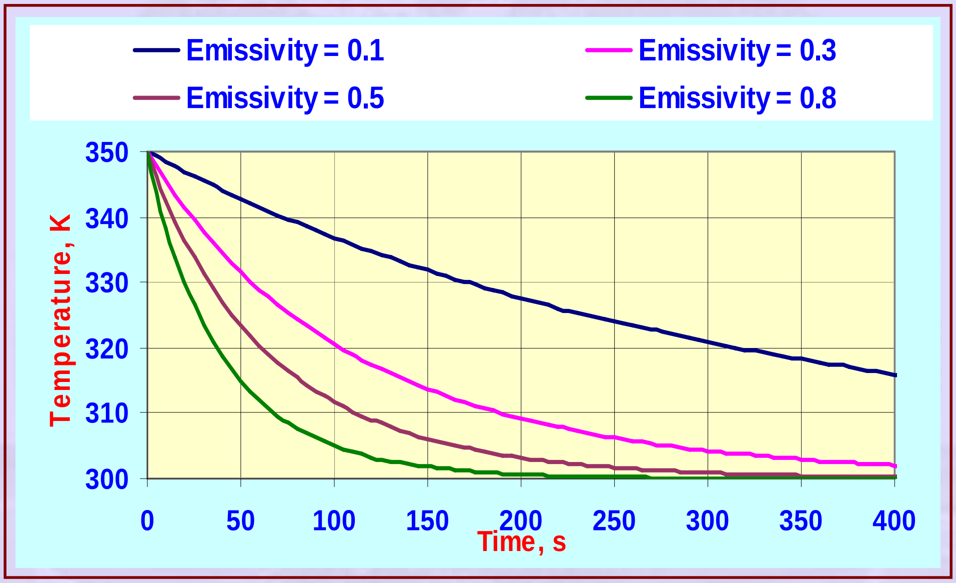

Figure 32 Cooing history of a heated object in vacuum

The unknown emissivity may be estimated by standard parameter estimation techniques, using, for example the least square method. If the measured temperature as function of time is represented by T_m and the simulated temperature obtained by solving Equation 28 as an initial value problem by assuming an emissivity value is T_s, then we require that

$$S = \sum_i \left(T_{s,i} - T_{m,i}\right)^2 \qquad \textbf{(29)}$$

be minimized. The minimization may be done by using non-linear least squares using a suitable method.

c) Calorimetric method of emissivity measurement:

Instead of the unsteady method described above one may use a steady sate calorimetric technique for the measurement of emissivity. The test surface is bonded on to a heater plate which is provided with temperature sensors. The plate is suspended in a vacuum chamber using very fine wires. The walls of the vacuum chamber are maintained at a low temperature by cooling them with liquid nitrogen (~ 77 K). The test plate is heated and brought to the desired steady temperature. The heat input to the plate (Q) is measured as also the temperature of the plate (T_p) and the walls of the vacuum chamber (T_w). The emissivity is then estimated by the relation

$$\varepsilon_h = \frac{Q}{\sigma\left(T_p^4 - T_w^4\right)} \qquad \textbf{(30)}$$

Any losses by conduction and residual convection may be estimated by performing the experiment with a surface of known emissivity. The heat loss may be estimated as a function of plate temperature and used as a correction on Q in the experiment with a surface of unknown emissivity.

d) Commercial portable ambient temperature emissometer:

This portable instrument for the measurement of emissivity near room temperature is supplied by the Devices & Services Company, Texas, U.S.A. If two surfaces are placed close to each other the heat transfer is proportional to the difference in fourth power of temperature and the emissivity of the two surfaces. If the gap is small compared to the size of the surface we have

$$q_{1-2} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \qquad \textbf{(31)}$$

Here the subscripts identify the two surfaces that face each other. Consider two surfaces with emissivities of ε_{high} and ε_{low} and at very nearly equal temperatures of T ($T_{high} \sim T_{low} \sim T$), and a third surface of emissivity ε and at ambient temperature T_∞. If these are arranged such that the first two surfaces exchange radiation with third surface, we have

$$q_{1-3} = \frac{\sigma\left(T_{high}^4 - T_\infty^4\right)}{\frac{1}{\varepsilon_{high}} + \frac{1}{\varepsilon} - 1},\; q_{2-3} = \frac{\sigma\left(T_{low}^4 - T_\infty^4\right)}{\frac{1}{\varepsilon_{low}} + \frac{1}{\varepsilon} - 1} \qquad \textbf{(32)}$$

Since the temperatures of the high and low emissivity surfaces are close to each other, the numerators of the two expressions in Equation 32 are practically equal. Because $\varepsilon_{high} > \varepsilon_{low}$ the denominator of q_{1-3} is smaller than the denominator of q_{2-3}. Hence q_{1-3} is greater than q_{2-3}. Because of this a small temperature difference exists between the surfaces 1 and 2. In the D&S emissometer the design is such that this temperature difference is proportional to the emissivity of the third surface, which will be the test surface.

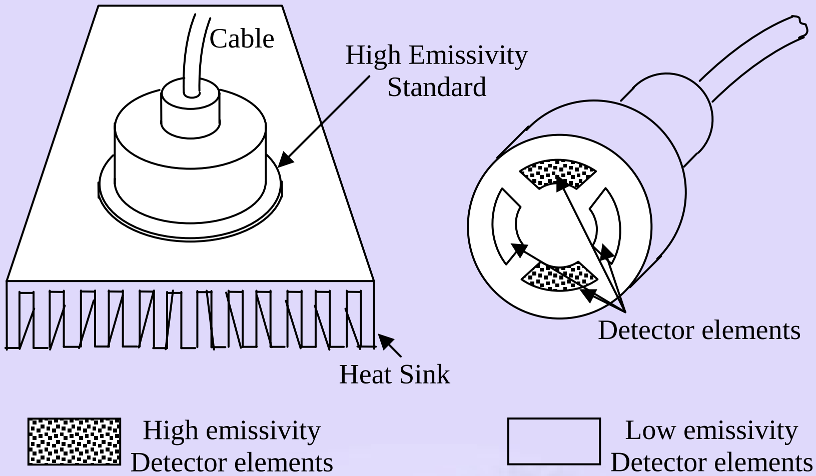

Figure 33 Schematic of the portable emissometer

Schematic of the D&S emissometer is shown in Figure 33. It consists of detector head which has four sectored radiation detectors as shown. The detectors are thermopiles with two sectors having high emissivity and the other two having low emissivity. The test specimen and the standard samples that are supplied with the emissometer are places on a heat sink as shown during the measurement process. The heat sink helps to maintain the samples at the room temperature. The detector head has cable connection for both heating the detector head and for taking out the differential output across the thermopiles.

In the emissometer the detector head is heated to about 355 K. The standard surfaces supplied with the instrument have diameter of 66.7 mm and thickness of 4 mm. The detector head views a 50 mm diameter area of specimen from a distance of 4.3 mm. The instrument output is connected to digital voltmeter that directly reads the emissivity of the specimen with two significant digits.

The instrument requires around 30 minutes of warm up time. The two standards are placed on the heat sink so that both of them attain the ambient temperature.

In order to have good thermal contact between the standards and the heat sink the air gaps are filled with distilled water. The detector head is then placed over the high emissivity standard and the gain of the voltmeter is adjusted so that it reads 0.89, after allowing about 90 s for equilibration. The detector head then placed over the low emissivity standard and the offset trimmer is adjusted such that the voltmeter reads 0.06. The adjustments are repeated till the emissometer may be moved from one standard and the other and the voltmeter readings indicate the two values without any adjustment.

The test specimen in the form and size similar to the standards are used for the emissivity determination. The specimen is placed on the heat sink and allowed to equilibrate with it. The detector head is placed over the specimen and the reading of the voltmeter directly gives the emissivity of the test surface.

The manufacturer specifications for the instrument are given in Table. 1.

Table 1 Specifications of Emissometer Model AE

Output	**2.4 mV nominal with a sample emissivity of 0.9 at 25°C**
Readout	**D&S Scaling Digital Voltmeter with resolution of 0.01 mV**
Output impedance	**150 , nominal**
Linearity	**Detector output linear with emissivity and to within ±0.01 emissivity**
Sample Temperature	**Maximum 55°C (328 K)**
Drift	**Negligible during measurement**
Time constant	**10 s, nominal**
Standards	**Four calibration standards are provided with the emissometer**