# Sub Module 2.5

# Pyrometery

Pyrometry is the art and science of measurement of high temperatures. According to the International Practical Temperature Scale 1968 (IPTS68) Pyrometry was specified as the method of temperature measurement above the gold point. Pyrometry makes use of radiation emitted by a surface (usually in the visible part of the spectrum) to determine its temperature. The measurement is thus a non-contact method of temperature measurement. We shall introduce basic concepts from radiation theory before discussing Pyrometry in detail.

## Radiation fundamentals

Black body radiation exists inside an evacuated enclosure whose walls are maintained at a uniform temperature. The walls of the enclosure are assumed to be impervious to heat transfer. The black body radiation is a function of the wavelength $\lambda$ and the temperature T of the walls of the enclosure. The amount of radiation heat flux leaving the surface, in a narrow band d$\lambda$ around$\lambda$, of the enclosure is called the spectral emissive power and is given by the Planck distribution function

$$E_{b\lambda}(T) = \frac{C_1}{\lambda^5}\frac{1}{e^{\frac{C_2}{\lambda T}} - 1} \quad (18)$$

$C_1$=First radiation constant = 3.742 x $10^8$ W $\mu m^4$ / $m^2$ and $C_2$ = Second radiation constant = 14390 $\mu$m K. It is seen that the wavelength is specified in $\mu$m (= $10^{-6}$ m). It is to be noted that there is no net heat transfer from the surface of an enclosure and hence it receives the same flux as it emits. It may also be seen that the -1 in the denominator is much smaller than the exponential term as long as $\lambda T << C_2$. This is indeed true in Pyrometry applications where the wavelength chosen is 0.65 μm and the measured temperature may not be more than 5000 K. It is then acceptable to approximate the Planck distribution function by the Wein's approximation given by

$$E_{b\lambda}(T) = \frac{C_1}{\lambda^5} e^{-\frac{C_2}{\lambda T}} \quad (19)$$

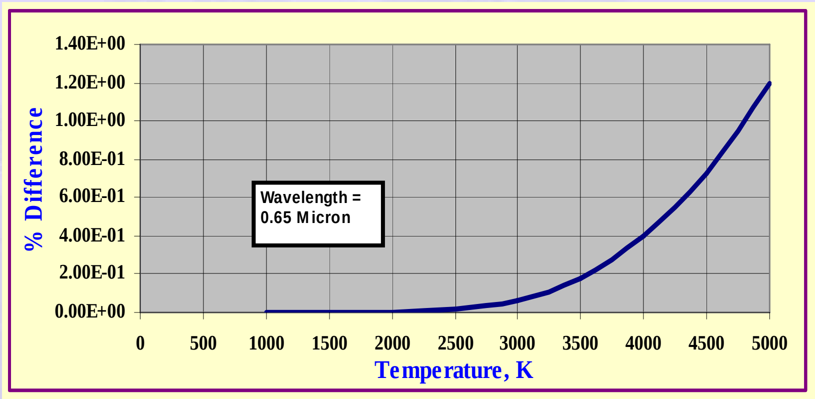


**Figure 34 Error in using approximate Wein's approximation instead of the Planck function**

It is clear from Figure 34 that the error in using the Wein's approximation in lieu of the Planck function is around 1% even at a temperature as high as 5000 K.

The spectral Black body emissive power has strong temperature dependence. In fact the emissive power peaks at a wavelength temperature product of

$$\lambda_{max} T = 2898 \ \mu m - K \quad (20)$$

This is referred to as Wein's displacement law. Figure 35 shows this graphically.

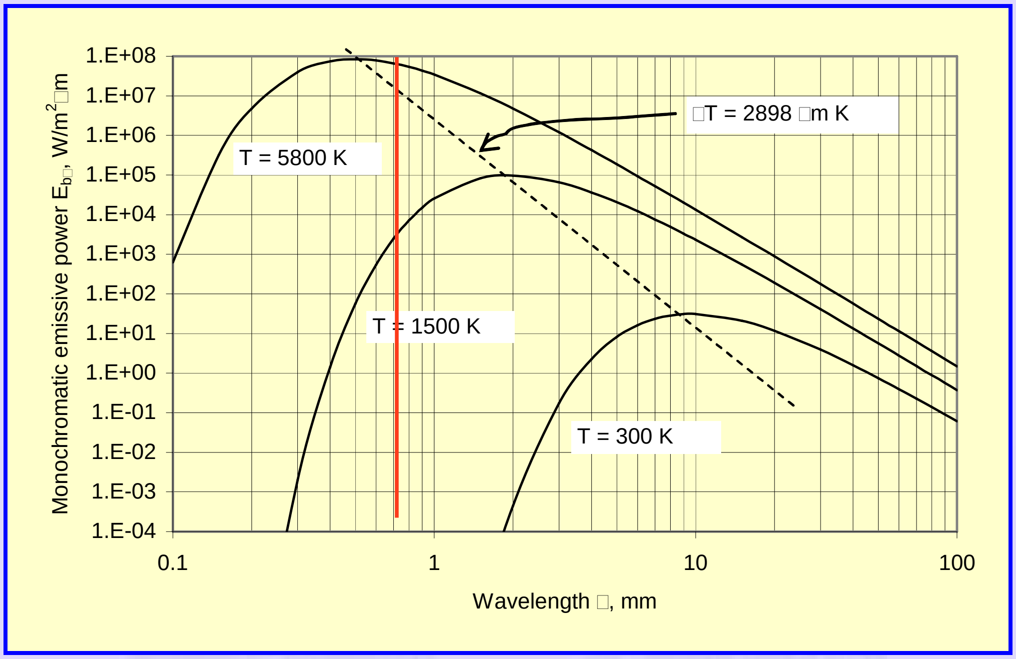


**Figure 35 Black body characteristics and the Wein's displacement law**
**(**Red line corresponds to a wavelength of 0.65 μm normally used in Pyrometry**)**

If you imagine keeping the wavelength fixed at say 0.65 μm, we see that the ordinate is a strong function of temperature! The surface will appear brighter to the eye higher the temperature. This is basically the idea central to Pyrometry. Actual surfaces, however, are not black bodies and hence they emit less radiation than a black surface at the same temperature. We define the spectral emissivity $\varepsilon_\lambda$ as the ratio of the emissive power of the actual surface to that from a black surface at the same temperature and wavelength.

$$\varepsilon_\lambda = \frac{E_{a\lambda}(T)}{E_{b\lambda}(T)} \quad (21)$$

## Brightness temperature

It is defined such that the spectral emissive power of the actual surface is the same as that of a hypothetical black body at the brightness temperature $T_B$. Thus:

$$E_{a\lambda}(T) = E_{b\lambda}(T_B) \quad (22)$$

If the emissivity of the surface (referred to as the target) is $\varepsilon_\lambda$, we use Equation 22 to write $\varepsilon_\lambda E_{b\lambda}(T) = E_{b\lambda}(T_B)$. Using Wein's approximation this may be re written as $\varepsilon_\lambda \frac{C_1}{\lambda^5} e^{-\frac{C_2}{\lambda T}} = \frac{C_1}{\lambda^5} e^{-\frac{C_2}{\lambda T_B}}$. We may cancel the common factor on the two sides, take natural logarithms, and rearrange to get

$$\frac{1}{T} - \frac{1}{T_B} = \frac{\lambda}{C_2} \ln(\varepsilon_\lambda) \quad \textbf{(23)}$$

Equation 23 is referred to as the ideal pyrometer equation. This relation relates the actual temperature of the target to the brightness temperature of the target. The brightness temperature itself is measured using a vanishing filament pyrometer. Equation 23 indicates that $T_B \le T$ since $\varepsilon_\lambda \le 1$ for any surface. In actual practice the intervening optics may introduce attenuation due to reflection of the radiation gathered from the target. It is also possible that one introduces attenuation intentionally as we shall see later. We account for the attenuation by multiplying the emissivity of the surface by a transmission factor $\tau_\lambda \le 1$ to get

$$\frac{1}{T} - \frac{1}{T_B} = \frac{\lambda}{C_2} \ln(\varepsilon_\lambda \tau_\lambda) \quad \textbf{(24)}$$

We refer to Equation 28 as the pyrometer equation.

We infer from the above that the brightness temperature of a surface depends primarily on the surface emissivity. If a surface is as bright as a black body at the gold point, the actual temperature should vary with spectral emissivity of the surface as indicated in Figure 36. Since no surface has zero emissivity we allow it to vary from 0.02 to 1 in this figure. As the spectral emissivity decreases the actual temperature increases as shown.

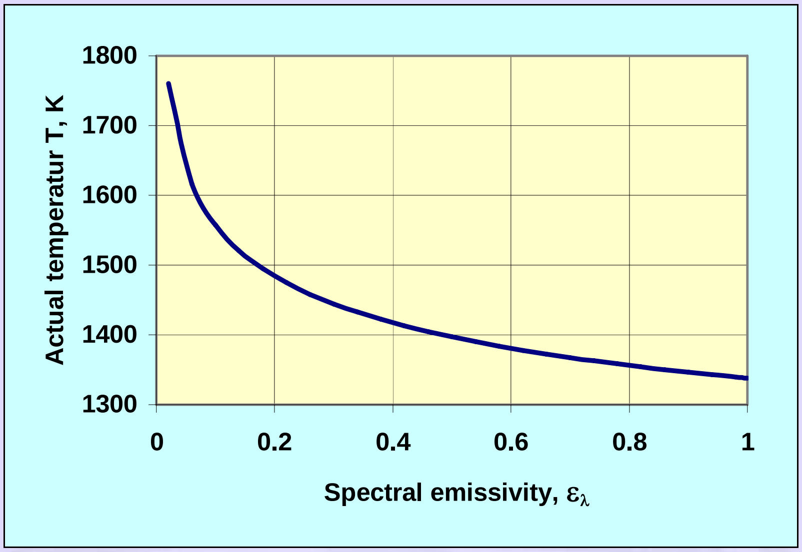


**Figure 36 Temperature a surface whose brightness temperature equals gold point temperature of 1337.6 K. $\lambda$ = 0.66 $\mu$m..**

Figure 36 also may be interpreted in a different way. Consider an actual surface whose spectral emissivity is known. If we introduce a transmission element with variable attenuation before making a comparison with a reference black body at the gold point, the abscissa in Figure 36 may be interpreted as the spectral emissivity transmission factor product. In that case the comparison is with respect to a single reference temperature, the gold point temperature. If this fixed point is determined with great precision on the ideal gas scale we have achieved measurement of an arbitrary temperature higher than the gold point temperature with reference to this single fixed point. This has the advantage that the pyrometer reference source (usually a standard tungsten filament lamp) runs at a constant temperature resulting in long life for the lamp.

**Black body reference – Cavity radiator**

Pyrometry requires a reference black body source that may be maintained at a desired temperature. This is achieved by making use of a black body cavity shown schematically in Figure 37.

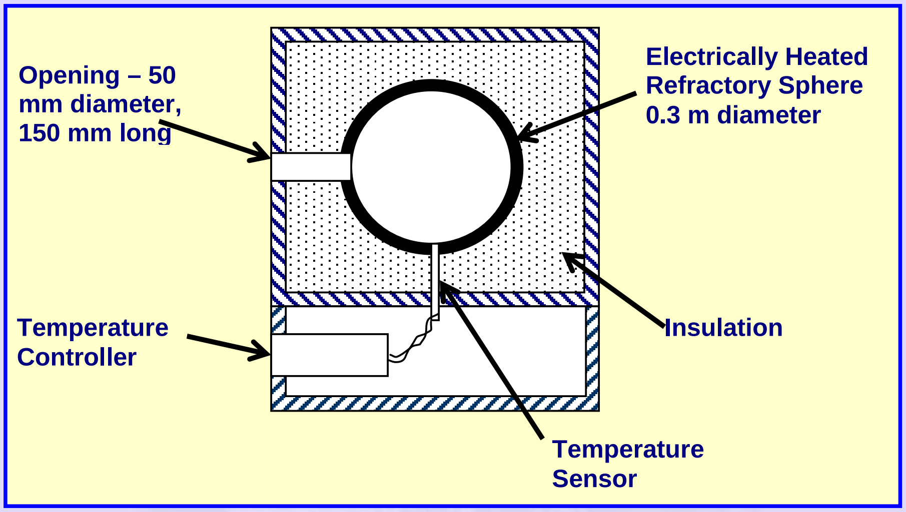


**Figure 37 Schematic of a black body furnace**

The black body reference consists of an electrically heated refractory sphere with a small opening as shown. The surface area of the sphere is much larger than the area of the opening through which radiation will escape to the outside. The radiation leaving through the opening is very close to being black body radiation at a temperature corresponding to the temperature of the inside of the sphere. Figure 22 shows that the effective emissivity of the opening is close to unity. The emissivity of the surface of the sphere is already high, 0.96, for the case shown in the figure). The area ratio for the case shown in Figure 31 is

$$\frac{A_{opening}}{A_{sphere}} = \frac{1}{4}\left(\frac{0.05}{0.3}\right)^2 \approx 0.007 \qquad (25)$$

The effective emissivity for this area ratio is about 0.995!

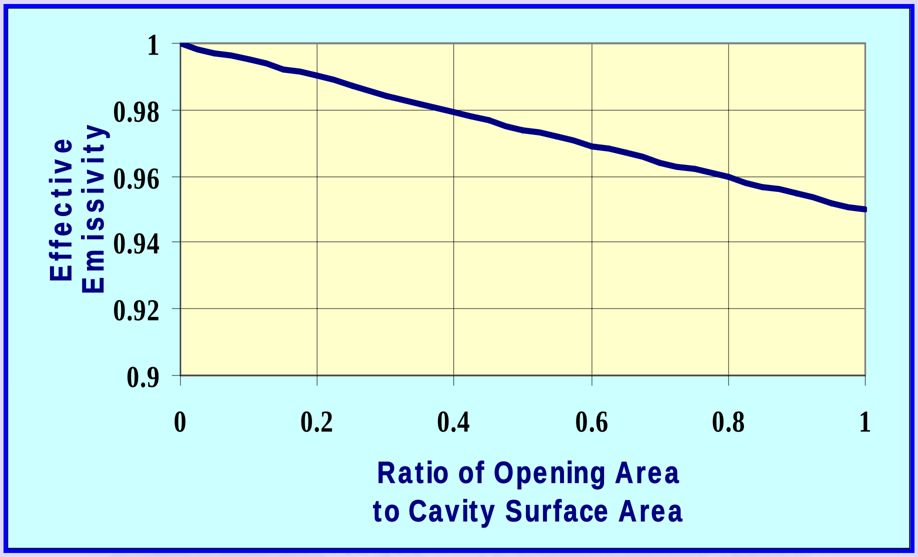


**Figure 38 Variation of effective emissivity of a cavity radiator with area ratio**

Many a time the cavity radiator has the sphere surrounded on the outside by a material undergoing phase change (solid to liquid). The melting point of the material will decide the exact temperature of the black body radiation leaving through the opening, as long as the material is a mixture of solid and liquid.

## Vanishing filament pyrometer

This is fairly standard equipment that is used routinely in industrial practice. The principle of operation of the pyrometer is explained by referring to the schematic of the instrument shown in Figure 39.

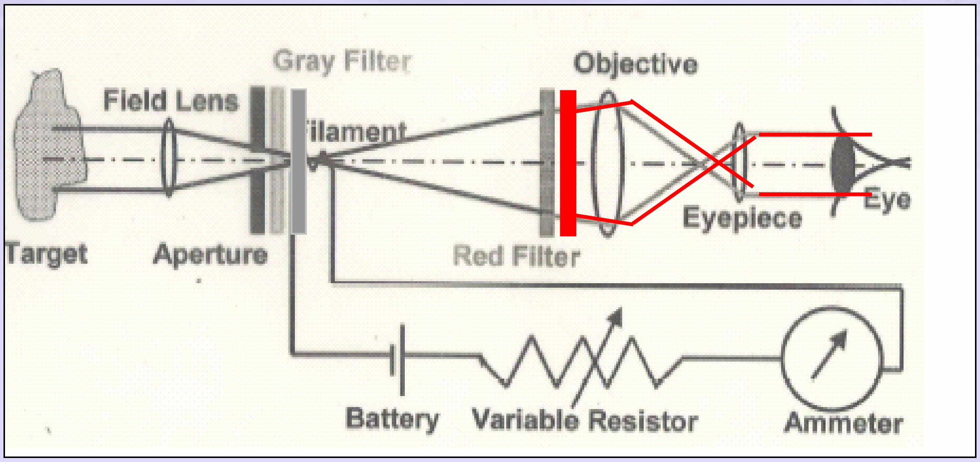


**Figure 39 Schematic of a vanishing filament pyrometer**

The pyrometer consists of collection optics (basically a telescope) to gather radiation coming from the target whose temperature is to be estimated. The radiation then passed through an aperture (to reduce the effect of stray radiation), a neutral density or grey filter (to adjust the range of temperature) and is brought to focus in a plane that also contains a source (tungsten filament standard) whose temperature may be varied by varying the current through it. The radiation from the target and the reference then passes through a red filter and is viewed by an observer as indicated in Figure 39. The observer will adjust the current through the reference lamp such that the filament brightness and the target brightness are the same. The state of affairs in the image seen by the eye of the observer is shown in Figure 40.

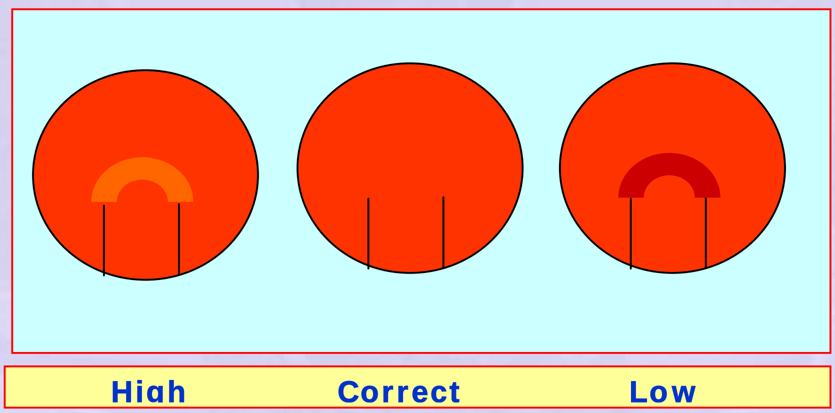


**Figure 40 Pyrometer adjustments**

If the adjustment is such that the filament is brighter than the target the setting is referred to as “high”. The filament appears as a bright object in a dull background. If the adjustment is such that the filament is duller than the target the setting is referred to as “low”. The filament appears as a dull object in a bright background. If the adjustment is “correct” the filament and the background are indistinguishable. Thus the adjustment is a null adjustment. The filament vanishes from the view! In this setting we have a match between the brightness of the target and the filament. The temperature of the filament is in deed the brightness temperature of the object. The wavelength corresponds to roughly a value of 0.66 μm. This is achieved by a combination of the response of the red filter and the eye of the observer (Figure 41). The average eye peaks around 0.6 μm and responds very poorly beyond 0.67 μm. The red filter transmits radiation beyond about 0.62 μm. On the whole the red filter – eye combination uses the radiation inside the red triangle shown in Figure 25. This region corresponds to a mean 0f 0.66 μm with a spectral width of approximately 0.03 μm.

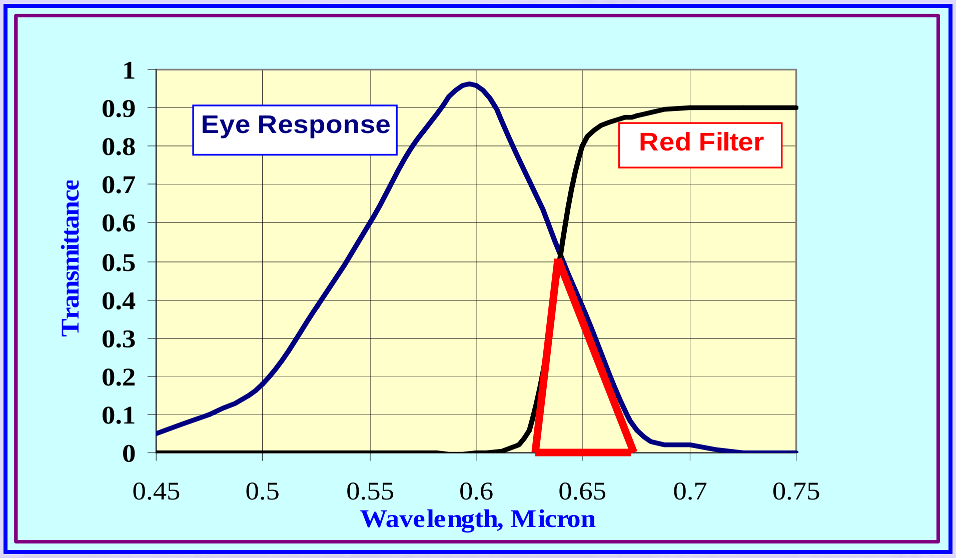


**Figure 41 Effective wavelength for the pyrometer**

## Example 12

- *A pyrometer gives the brightness temperature of an object to be 800$^o$C. The optical transmittance for the radiation collected by the pyrometer is known to be 0.965 and the target emissivity is 0.260. Estimate the temperature of the object. Take $\lambda$ = 0.655 $\mu$m as the effective wavelength for the pyrometer.*

  - *Given data:*
    - $\lambda = 0.655\ \mu\text{m},\ C_2 = 14390\ \mu\text{m}-\text{K},\ \tau = 0.965,\ T_b = 800°\text{C} = 1073\ \text{K}$
  - *Target emissivity is*
    - $\varepsilon = 0.260$
  - *The emissivity transmittivity product is*
    - $\varepsilon\tau = 0.260 \times 0.965 = 0.251$
  - *Using the pyrometer equation, we get:*
    - $$T_a = \frac{1}{\frac{1}{T_b} + \frac{\lambda}{C_2}\ln(\varepsilon\tau)} = \frac{1}{\frac{1}{1073} + \frac{0.655}{14390} \times \ln(0.251)} = 1151\ \text{K}$$

## Example 13

- *The brightness temperature of a metal block is given as 900°C. A thermocouple embedded in the block reads 1015°C. What is the emissivity of the surface? The pyrometer used in the above measurement is a vanishing filament type with an effective $\lambda$ of 0.65 $\mu$m. Assuming that the thermocouple reading is susceptible to an error of ±10°C while the brightness temperature is error free determine an error bar on the emissivity determined above.*

- *The first and second radiation constants, in SI units are:*

$$C_1 = 3.743\times10^{-16}\ \mathrm{W\,m^2},\ C_2 = 14387\ \mu\mathrm{m-K}$$

- *The data specifies the actual ($T_a$) as well as the brightness ($T_b$) temperatures and it is desired to determine the emissivity of the metal block at the stated wavelength.*

$$\lambda = 0.65\ \mu\mathrm{m},\ T_a = 1015°C = 1288\,K, T_b = 900°C = 1173\ K$$

- *We make use of the pyrometer equation to estimate $\varepsilon$.*

$$\varepsilon = \exp\left[\frac{\frac{1}{T_a} - \frac{1}{T_b}}{\frac{\lambda}{C_2}}\right] = \exp\left[\frac{\frac{1}{1288} - \frac{1}{1173}}{\frac{0.65}{14387}}\right] = 0.185$$

- *This is the nominal value of the emissivity.*
- *The error in $\varepsilon$ is due to error in $T_a$. This is calculated using the standard method discussed in the class. We need to calculate the derivative of $\varepsilon$ with respect to $T_a$.*

$$\frac{d\varepsilon}{dT_a} = \frac{d}{dT_a}\left[\frac{C_2}{\lambda}\left\{\frac{1}{T_a} - \frac{1}{T_b}\right\}\right]\times\exp\left[\frac{\frac{1}{T_a} - \frac{1}{T_b}}{\frac{\lambda}{C_2}}\right] = \frac{C_2}{\lambda}\left(-\frac{1}{T_a^2}\right)$$

$$= -\frac{14387}{0.65}\times\frac{1}{1288^2}\times0.185 = -0.00247/K$$

- *Since* $\Delta T_a = \pm 10\ \mathrm{K}$, *the error in emissivity is given by*

$$\Delta\varepsilon = \frac{d\varepsilon}{dT_a}\Delta T_a = -0.00247 \times \pm 10 \approx \mp 0.025$$

## Emissivity values

Temperature measurement using a pyrometer requires that the surface emissivity of the target be known. Useful emissivity data is given in Table 11. These are representative values since the nature of the surface is application specific and much variation is possible. One way out of this is to perform an experiment like the one presented in Example 13.

**Table 11Approximate emissivity values**

| | Temperature °C | | | |
|---|---|---|---|---|
| **Surface** | **600** | **1200** | **1600** | **1800** |
| Iron, Un-oxidized | 0.2 | 0.37 | | |
| Iron, Oxidized | 0.85 | 0.89 | | |
| Molten Cast Iron | | | 0.29 | |
| Molten Steel | | | 0.28 | 0.28 |
| Nickel, Oxidized | | 0.75 | 0.75 | |
| Fireclay | | 0.52 | 0.45 | |
| Silica Bricks | | 0.54 | 0.46 | |
| Alumina Bricks | | 0.23 | 0.19 | |

In fact one may vary the surface temperature over a range of values that is expected to occur in a particular application and the measure the emissivity values over this range. An emissivity table may then be made for later use. Uncertainty in emissivity affects the measurement of temperature using a pyrometer. Figure 42 shows a plot of temperature error as a function of emissivity error, both in percent. For small errors the relationship is almost linear with $\Delta T_a = 0.65\Delta\varepsilon$. The case considered is a vanishing filament pyrometer operating at 0.65 μm.

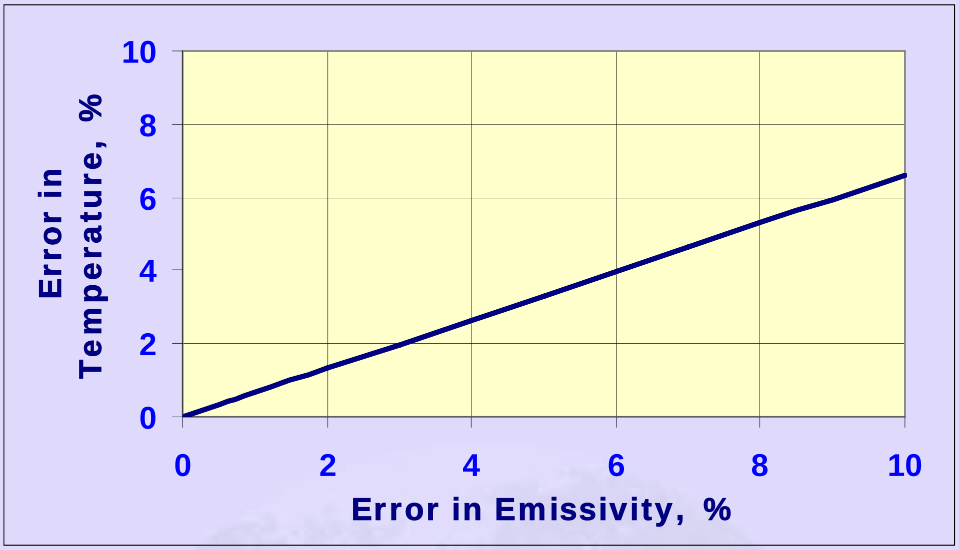


**Figure 42 Effect of uncertainty in emissivity on pyrometer measurement of temperature**

## Ratio Pyrometry and the two color pyrometer

Uncertainty in target emissivity in the case of vanishing filament pyrometer is a major problem. This makes one look for an alternate way of performing pyrometric measurement, based on the concept of color or ratio temperature. Consider two wavelengths $\lambda_1$ and $\lambda_2$ close to each other. Let the corresponding emissivity values of the target be $\varepsilon_1$ and $\varepsilon_2$. The color temperature $T_c$ of the target is defined by the equality of ratios given by

$$\frac{E_{a\lambda_1}(T_a)}{E_{a\lambda_2}(T_a)} = \frac{E_{b\lambda_1}(T_c)}{E_{b\lambda_2}(T_c)} \qquad \textbf{(26)}$$

**Thus it is the temperature of a black body for which the ratio of spectral emissive powers at two chosen wavelengths $\lambda_1$ and $\lambda_2$ is the same as the corresponding ratio for the actual body.**

We may use the Wein's approximation and write the above as

$$\frac{\varepsilon_1 \exp\left[-\frac{C_2}{\lambda_1 T_a}\right]}{\varepsilon_2 \exp\left[-\frac{C_2}{\lambda_2 T_a}\right]} = \frac{\exp\left[-\frac{C_2}{\lambda_1 T_c}\right]}{\exp\left[-\frac{C_2}{\lambda_2 T_c}\right]} \text{ or } \frac{\varepsilon_1}{\varepsilon_2}\exp\left[-\frac{C_2}{T_a}\left\{\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right\}\right] = \exp\left[-\frac{C_2}{T_b}\left\{\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right\}\right]$$

Taking natural logarithms, we have

$$\ln\frac{\varepsilon_1}{\varepsilon_2}-\frac{C_2}{T_a}\left[\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right]=-\frac{C_2}{T_c}\left[\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right]$$

This may be rearranged as

$$\frac{1}{T_a}-\frac{1}{T_c}=\frac{1}{C_2}\frac{\ln\frac{\varepsilon_1}{\varepsilon_2}}{\frac{1}{\lambda_1}-\frac{1}{\lambda_2}} \qquad (27)$$

This equation that links the color and actual temperatures of the target is the counterpart of Equation 23 that linked the brightness and actual temperatures of the target. In case the emissivity does not vary with the wavelength we see that the color and actual temperatures are equal to each other. We also see that the actual temperature may be either less than or greater than the color temperature. This depends solely on the ratio of emissivities at the two chosen wavelengths. Equation 27 by itself is not directly useful. We measure the ratio of emissive powers of the target, at its actual temperature, at the two chosen wavelengths. Thus what is measured is the ratio occurring on the left hand side of Equation 26. Thus we have

$$\frac{E_{a\lambda_1}}{E_{a\lambda_2}}=\frac{\varepsilon_1}{\varepsilon_2}\frac{\lambda_2^5}{\lambda_1^5}\frac{\exp\left[\frac{C_2}{\lambda_1 T_a}\right]}{\exp\left[\frac{C_2}{\lambda_2 T_a}\right]}$$

Again we may take natural logarithms to get

$$T_a=\frac{C_2\left(\frac{1}{\lambda_2}-\frac{1}{\lambda_1}\right)}{\ln\left[\frac{E_{a\lambda1}\lambda_1^5\varepsilon_2}{E_{a\lambda2}\lambda_2^5\varepsilon_1}\right]} \qquad (28)$$

Similarly we may show that

$$T_c=\frac{C_2\left(\frac{1}{\lambda_2}-\frac{1}{\lambda_1}\right)}{\ln\left[\frac{E_{a\lambda1}\lambda_1^5}{E_{a\lambda2}\lambda_2^5}\right]} \qquad (29)$$

Equation 28 is useful as a means of estimating the actual temperature for a target, whose emissivities at the two chosen wavelengths are known, and the measured values of emissive powers at the two wavelengths are available. The instrument that may be used for this purpose is the two color pyrometer whose schematic is shown in Figure 43.

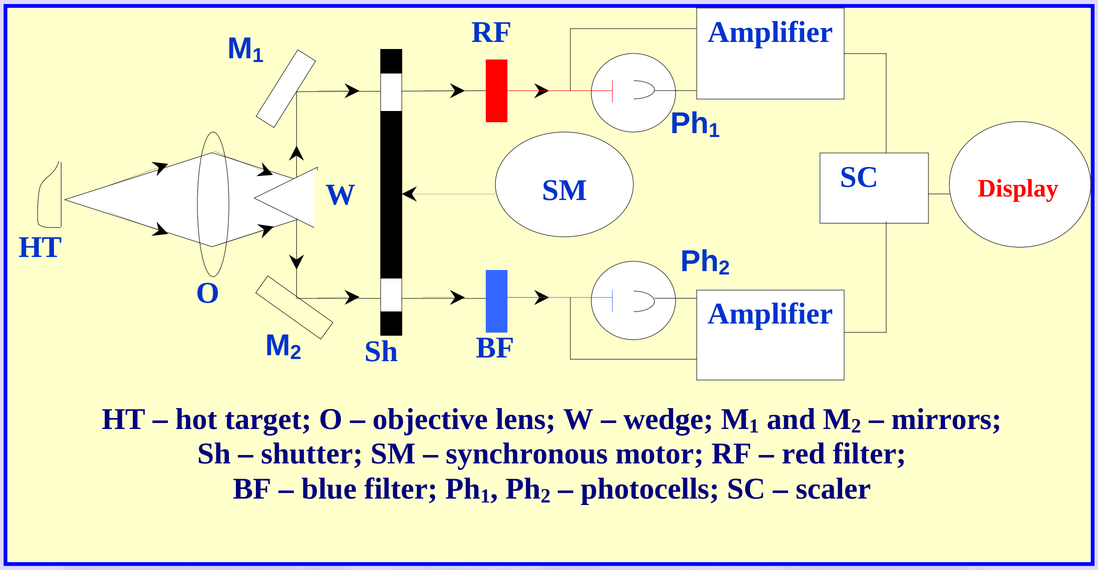


**Figure 43 Schematic of a two color pyrometer**

The radiation from the target is split up in to two beams by the use of a wedge, as indicated. Two mirrors redirect the two beams as shown. These pass through a rotating wheel with openings, as indicated. The beams then pass through two filters that allow only a narrow band around a well defined wavelength (indicated as red and blue). The rotating wheel chops the two beams and creates ac signal to be detected by the photocells. The ratio of the two signals is equal to the ratio of emissive powers in Equation 28. The scaler introduces the other ratios that appear in the same equation. The display then indicates the actual temperature.

# Example 14

- *A certain target has a brightness temperature of 1000 K when viewed by a vanishing filament pyrometer. The target emissivity at 0.66  m is known to be 0.8. What is the true temperature of the target? What is the colour temperature of the same target if* $\lambda_1 = 0.66\ \mu\text{m},\ \lambda_2 = 0.5\ \mu\text{m},\ \varepsilon_{\lambda_2} = 0.50$ *?*

- *Given Data:* $T_B = 1000\ \text{K},\ \lambda_1 = 0.66\ \mu\text{m},\ \varepsilon_{\lambda_1} = 0.8$
- *The ideal pyrometer equation may be recast to read as*

$$T_a = \frac{1}{\dfrac{1}{T_B} + \dfrac{\lambda_1}{C_2}\ln\left(\varepsilon_{\lambda_1}\right)}$$

- *Thus the true target temperature is*

$$T_a = \frac{1}{\dfrac{1}{1000} + \dfrac{0.66}{14390}\ln\left(0.8\right)} = 1010.3\ \text{K}$$

- *For determining the colour temperature the required data is:*

$$\lambda_1 = 0.66\ \mu\text{m},\ \varepsilon_{\lambda_1} = 0.8$$
$$\lambda_2 = 0.5\ \mu\text{m},\ \varepsilon_{\lambda_2} = 0.5$$

- *We determine the color temperature by using the relation*

$$T_c = \frac{1}{\left[\dfrac{1}{T_a} - \dfrac{\ln\left(\dfrac{\varepsilon_{\lambda_2}}{\varepsilon_{\lambda_1}}\right)}{C_2\left(\dfrac{1}{\lambda_2} - \dfrac{1}{\lambda_1}\right)}\right]}$$

$$= \frac{1}{\left[\dfrac{1}{1010.3} - \dfrac{\ln\left(\dfrac{0.76}{0.86}\right)}{14390 \times \left(\dfrac{1}{0.5} - \dfrac{1}{0.66}\right)}\right]} = 969.7\text{K}$$