2.6 Blackbody Radiation

黑体辐射

Many commonly encountered light sources, including the sun and incandescent light bulbs, are closely modelled as "blackbody" emitters. A blackbody absorbs all radiation incident on its surface and emits radiation based on its temperature. Blackbodies derive their name from the fact that, if they do not emit radiation in the visible range, they appear black due to the complete absorption of all wavelengths. The blackbody sources which are of interest to photovoltaics, emit light in the visible region. The spectral irradiance from a blackbody is given by Planck's[1] radiation law, shown in the following equation:

$$F(\lambda)=\frac{2\pi hc^2}{\lambda^5\left[\exp\left(\frac{hc}{k\lambda T}-1\right)\right]}$$

where:

λ is the wavelength of light;

T is the temperature of the blackbody (K);

F is the spectral irradiance in $W/m^2/\mu m$; and

h, c and k are constants.

我们常见的很多光源，包括太阳和白炽灯，都可以用黑体模型准确的描述。黑体吸收一切入射到它表面的辐射并基于它本身的温度向外辐射。如果物体吸收所有波长的光而它发出的波又不在可见光区域内，它就会呈现出黑色，这种物体就被称为黑体。光伏领域所感兴趣的是黑体辐射出的在可见光区域内的波。黑体的光谱幅照度由普朗克的辐射定律给出，公式如下所示：

$$F(\lambda)=\frac{2\pi hc^2}{\lambda^5\left[\exp\left(\frac{hc}{k\lambda T}-1\right)\right]}$$

公式中：

λ表示光的波长；

T表示黑体的温度（单位：开尔文）；

F表示光谱幅照度（单位：瓦每平方米每微米）；

h，c和k均为常数。

Getting the correct result requires care with the units. The simplest is to use SI units so that c is in m/s, h is in joule·seconds, T is in kelvin, k is in joule/kelvin, and λ is in meters. This will give units of spectral irradiance in W/m^3. Dividing by 10^6 gives the conventional units of spectral irradiance in $W/m^2/\mu m$. The notation of $F(\lambda)$ denotes that the spectral irradiance changes with wavelength.

如果想通过上述公式得到正确的结果，在处理各个量的单位时就得非常小心。最简单的方法就是采用国际单位制，这样一来，光速的单位为米每秒，普朗克常量的单位是焦耳·秒，温度的单位是开尔文，波尔兹曼常数的单位是焦耳每开，波长的单位是米。采用这些单位计算得到的光谱幅照度的单位是瓦每立方米。再除以 10 的 6 次方，我们就可以得到用常用的单位（瓦每平方米每微米）表示的光谱幅照度的值。函数$F(\lambda)$表示光谱幅照度是波长的函数。

The total power density from a blackbody is determined by integrating the spectral irradiance over all wavelengths which gives:

$$H = \sigma T^4$$

where σ is the Stefan-Boltzmann constant and T is the temperature of the blackbody in kelvin.

黑体的总功率密度是通过在整个波长范围上对光谱幅照度积分得到的，公式如下所示：

$$H = \sigma T^4$$

公式中的σ为斯蒂芬-波尔兹曼常数，T为黑体的绝对温度（单位：开尔文）。

An additional important parameter of a blackbody source is the wavelength where the spectral irradiance is the highest, or, in other words the wavelength where most of the power is emitted. The peak wavelength of the spectral irradiance is determined by differentiating the spectral irradiance and solving the derivative when it equals 0. The result is known as Wien's Law and is shown in the following equation:

$$\lambda_p(\mu m) = \frac{2900}{T}$$

where λ_p is the wavelength where the peak spectral irradiance is emitted and

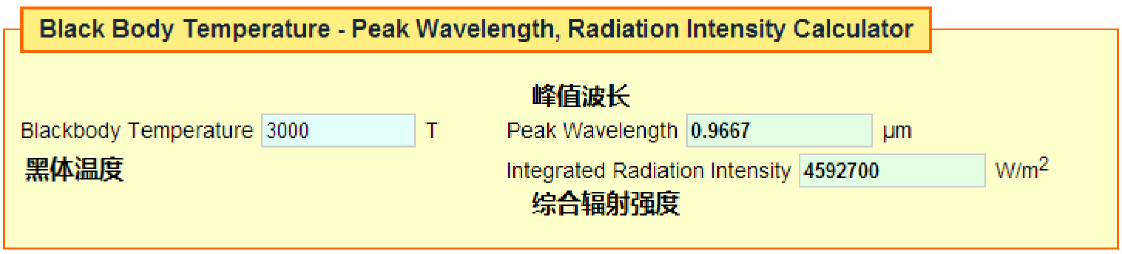
T is the temperature of the blackbody (K).

黑体的另一个重要参数为光谱幅照度的峰值对应的波长，换言之，该波长辐射出的能量最多。通过对光谱幅照度求导，导数值为 0 处的波长即为峰值波长。求导的结果称为维恩定律，公式如下所示：

$$\lambda_p(\mu m) = \frac{2900}{T}$$

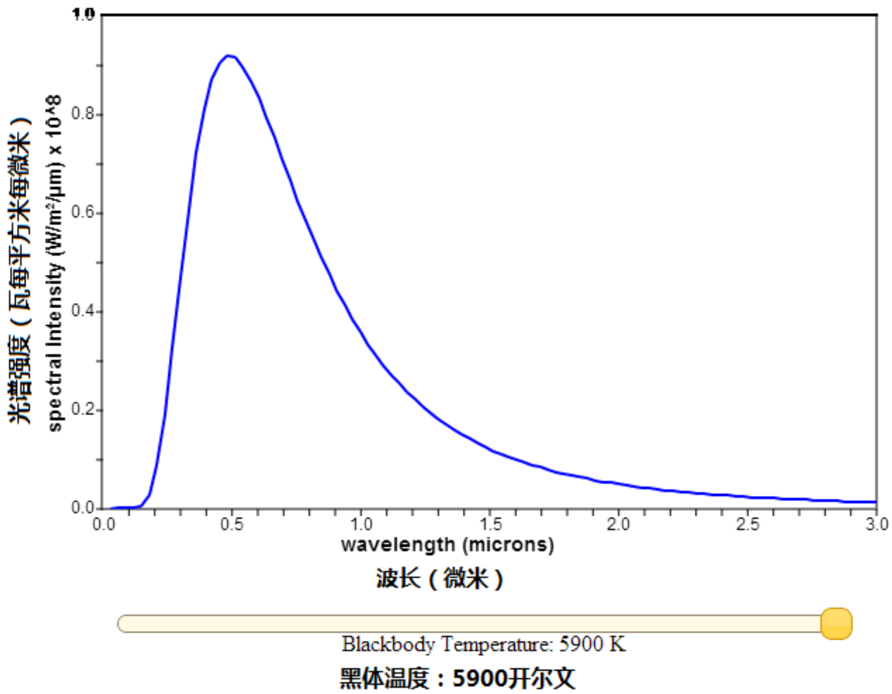
公式中，λ_p表示峰值波长，T表示黑体的绝对温度（单位：开尔文）。

黑体温度-波长峰值，辐射强度计算器



Drag the slider at the bottom of the graph to see the change in the blackbody radiation spectrum as the temperature is increased from 1000 to 6000 K.

拖动下图底部的滑块可以看到当温度从 1000 开尔文上升到 6000 开尔文时，黑体辐射谱的变化情况。

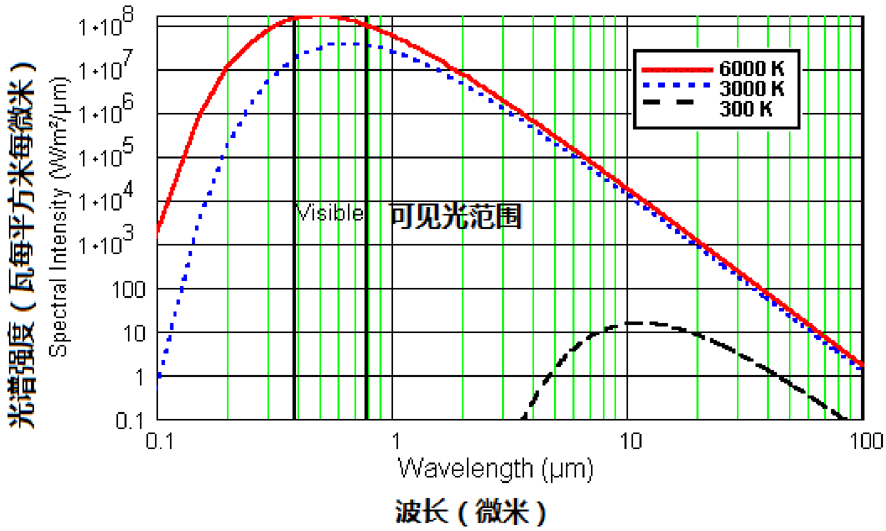


Moving the slider to higher temperature causes a substantial increase in the emission and the peak to shift to shorter wavelengths.

移动滑块至高温会导致辐射的显著增强，峰值波长会向短波移动。

The above equations and animation show that as the temperature of a blackbody increases, the spectral distribution and power of light emitted change. For example, near room temperature, a blackbody emitter (such as a human body or light bulb which is turned off) will emit low power radiation at wavelengths predominantly greater than 1µm, well outside the visual range of human observation. If the blackbody is heated to 3000 K, it will glow red because the spectrum of emitted light shifts to higher energies and into the visible spectrum. If the temperature of the filament is further increased to 6000 K, radiation is emitted at wavelengths across the visible spectrum from red to violet and the light appears white. The graphs below compare the spectral irradiance of a blackbody at these three temperatures. The room temperature case of 300K (the black dotted line) has essentially no power emitted in the visible and near infrared portions of the spectrum shown on the graph. Because of the huge variation in both emitted power and the range of wavelengths over which the power is emitted, the log graph below demonstrates more clearly the variation in the emitted blackbody spectrum as a function of temperature.

上述公式和动画表明，当黑体的温度上升时，它的光谱分布和光的功率会发生变化。举例来说，当黑体的温度接近室温时（比如人体或者关掉的灯泡），它所发出的低功率辐射的波长主要集中于大于 1 微米的波段范围，远在人眼的观测范围之外。如果黑体被加热到 3000 开尔文，光谱会向高能量方向移动，进入可见光光谱范围，黑体会发出红光。如果灯丝的温度被进一步加热到 6000 开尔文，它的辐射将包含整个可见光光谱，从红色到紫色。这时，灯就会发出白光。下图比较了黑体在 3 种温度下的光谱幅照度。如图所示，当黑体温度为 300K（室温）时（在图中用黑色点线表示），辐射出的功率不在可见光范围内而在整个光谱的近红外部分。因为辐射出的功率及其对应的波长范围的变化很大，下图采用了双对数坐标以更清楚地显示黑体辐射光谱随温度变化的情况。



Spectral intensity of light emitted from a black body on a log-log scale. At room temperature the emission is very low and centered around 10 µm.

上图为双对数坐标下，黑体发出的光的光谱强度。在室温下，辐射强度很低，并且集中在波长为 10 微米的范围。

参考文献

1. Planck M. Distribution of energy in the spectrum. Annalen der Physik. 1901;4:553-563.