Arif Iqbal Mallick,
Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

Paper: C14T (Statistical Mechanics)
Topic: Classical Theory of Radiation

Today we are going to discuss the classical theory of radiation. The content of the discussion will be as following:

- Introduction to Thermal Radiation
- Introduction to Blackbody and its Radiation
- Analogy between Blackbody Radiation and Ideal Gas
- Emissive Power and Absorptive Power
- Kirchhoff's Law and its Applications

Thermal Radiation

Thermal radiation is electromagnetic in nature and is generated by thermal motion of particles in matter. All matter with temperature above absolute zero emits thermal radiation. Particle motion in matter due to thermal energy results in charge acceleration or dipole oscillation which generates electromagnetic radiation called thermal radiation. It is emitted by a heated surface in all directions and travels with the speed of light till it gets absorbed by some surface. Thermal radiation does not require any medium to propagate.

Thermal radiation has wavelengths ranging from the longest infrared wavelength to the shortest ultraviolet wavelength through the visible-light spectrum. The intensity and the distribution of radiant energy depend on the temperature of the emitting surface. The total radiant heat energy emitted by a surface is proportional to the fourth power of absolute temperature as described by *Stefan-Boltzmann law* which we will discuss in the following section.

The rate of thermal radiation (or absorption) from (or by) a body depends upon the nature of the surface as well. A body which is a good emitter is also a good absorber according to *Kirchhoff's radiation law*. For example, a blackened surface is a very good emitter as well as a very good absorber. Whereas a silvered surface is a poor emitter and a poor absorber of thermal radiation.

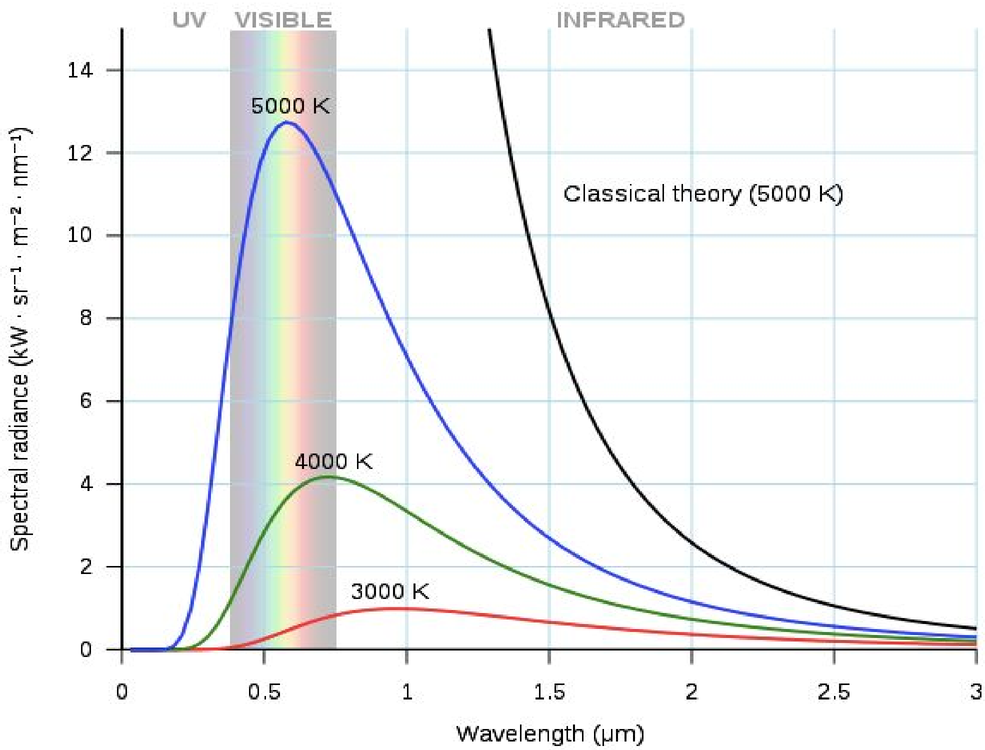
The heating of the Earth by the Sun is an example of energy transfer through thermal radiation. Infrared radiation emitted by animals is another example of thermal radiation. Thermal radiation is one of the fundamental mechanisms of heat transfer.

Blackbody Radiation

A blackbody is an idealized physical object that absorbs all incident electromagnetic radiations irrespective of frequency or angle of incidence. Such a perfect absorber is also a perfect emitter of electromagnetic radiation. But, a blackbody does not reflect any radiation at all. The name "blackbody" is given because it absorbs electromagnetic radiations of ALL frequencies.

Blackbody radiation is the thermal radiation emitted by a blackbody in thermodynamic equilibrium with its environment. It has a spectrum of wavelengths, inversely related to intensity that depends only on the temperature of the blackbody. The spectral distribution of the thermal energy radiated by a blackbody is shown in the figure below.

The thermal radiations which are spontaneously emitted by many ordinary objects can be approximated as blackbody radiations. A perfectly insulated enclosure which is in thermal equilibrium internally (i.e. at a constant temperature) contains blackbody radiation and it can emit the radiation through a hole made in its wall, provided the hole is small enough so that it does not affect the equilibrium of the enclosure. So, such an enclosure can be called a blackbody.



As the temperature increases, the peak of the blackbody radiation curve moves to higher intensities and smaller wavelengths.

Analogy between Blackbody Radiation and Ideal Gas:

The blackbody radiation and an ideal gas possess some fundamental similarities. That is why some of the ordinary thermodynamic relations can be applied to the blackbody radiation. The similarities are as following:

(i) An ideal gas is an assembly of particles (atoms or molecules) in perfect chaos i.e. having all velocities ranging from 0 to ∞ and moving in all directions. Similarly, the radiations from an enclosure at a constant temperature (blackbody) have all possible wavelengths and propagate in all directions.

(ii) The atoms or molecules of an ideal gas exert a pressure on the walls of the container. The blackbody radiations also exert pressure on the surface placed normally to the radiation direction.

(iii) Ideal gas consists of particles having kinetic energies ranging from 0 to ∞. Similarly, the blackbody radiation consists of quanta (photons) of energies ranging from 0 to ∞.

(iv) The internal energy of an ideal gas is equivalent to the energy density of blackbody radiation.

Kirchhoff's Law

Before we discuss Kirchhoff's law of electromagnetic radiations, we will define two important quantities - (i) Emissive Power and (ii) Absorptive Power.

(i) Emissive Power: The emissive power e_λ of a body for the radiation of wavelength between λ and $\lambda+d\lambda$ is defined as the amount of radiation emitted per unit area of the body per second in unit solid angle in the direction along the axis of the solid angle.

The emissive power of a body is a function of λ and has a spectral nature. The total emissivity or total emissive power E is given by

$$E = \int_0^\infty e_\lambda \, d\lambda \qquad \text{——— (1)}$$

(ii) Absorptive Power: If dQ_λ be the amount of radiant energy falling on a body in the form radiation in the wavelength range λ to $\lambda+d\lambda$ and a fraction $a_\lambda dQ_\lambda$ of it is absorbed by the body and converted into heat, then a_λ is called the absorptive power of the body for the wavelength λ to $\lambda+d\lambda$.

Arif Iqbal Mallick, Asst. Prof.,
Dept. of Physics, Narajole Raj College, Narajole.

By the definition, absorptive power (a_λ) of a blackbody is 1 for radiation of any wavelength. We give a special notation to the emissive power of a blackbody as E_λ.

Kirchhoff's law states that *the ratio of the emissive power to the absorptive power for the radiation of a given wavelength is the same for all bodies at the same temperature. The ratio is equal to the emissive power of a blackbody at that temperature. Symbolically,*

$$\frac{e_\lambda}{a_\lambda} = \text{constant} = E_\lambda \quad \text{——} (2)$$

where E_λ is the emissive power of a blackbody. Equation (2) is the mathematical form of Kirchhoff's law.

The importance of Kirchhoff's law has two distinct aspects - (i) qualitative and (ii) quantitative. Qualitatively it says that if a body is capable of emitting radiations of certain wavelengths then it can also absorb them when they are incident on it. Quantitatively, it describes that the ratio of the emissive power to the absorptive power is constant for all bodies at a constant temperature. Kirchhoff's law opened up two new branches of Physics/Science - (i) **Astrophysics** and (ii) **Spectroscopy**. It has still very far reaching consequences. It asserts that every different atom, when excited properly, emits radiation (light) of a different wavelength which is characteristic of the atom. Hence each atom can be identified by the particular line it emits. This method of identifying elements is called ***Spectral Analysis***. By this method many new elements have been discovered and added to the periodic table.

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Dept. of Physics, Narajole Raj College, Narajole.

References:

1. https://en.wikipedia.org/wiki/Thermal_radiation
2. https://en.wikipedia.org/wiki/Black-body_radiation
3. Thermal Physics (Heat and Thermodynamics) - A B Gupta and H P Roy

[Figures taken from above websites are used for teaching purposes only.]