THERMAL ENGINEERING-II

Keeping in view of the Pandemic COVID 19 , the regular classes have been stopped. Importance is being given to give handouts to the students and to conduct online classes. In a short time I have prepared this notes for benefit of the students and I hope, it will be interesting, as if two way of communication between you and me. This is the last chapter of of our curriculum in Thermal Engg II

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Syllabus

Chapter 6

Heat transfer

i. Modes of Heat transfer (Conduction, convection, Radiation)
ii. Fourier law of heat conduction and thermal conductivity
iii. Newton’s law of cooling
iv. Radiation heat transfer (Stefan Boltzman law, Kirchoff law only statement)
v. Black body radiation

MODES OF HEAT TRANSFER

- Whenever temperature difference exists in a medium or between media Heat transfer must occur. We refer mode as different types of heat transfer process.
- When a temperature gradient exists in a stationary medium, which may be a solid or a fluid, we use the term conduction mode of heat transfer.
- convection mode of heat transfer refers to heat transfer that will occur between a surface and a moving fluid when they are at different temperatures
- The third mode of heat transfer is termed thermal radiation. All surfaces of finite temperature emit energy in the form of electromagnetic waves. Hence, in the absence of an intervening medium, there is net heat transfer by radiation between two surfaces at different temperatures.

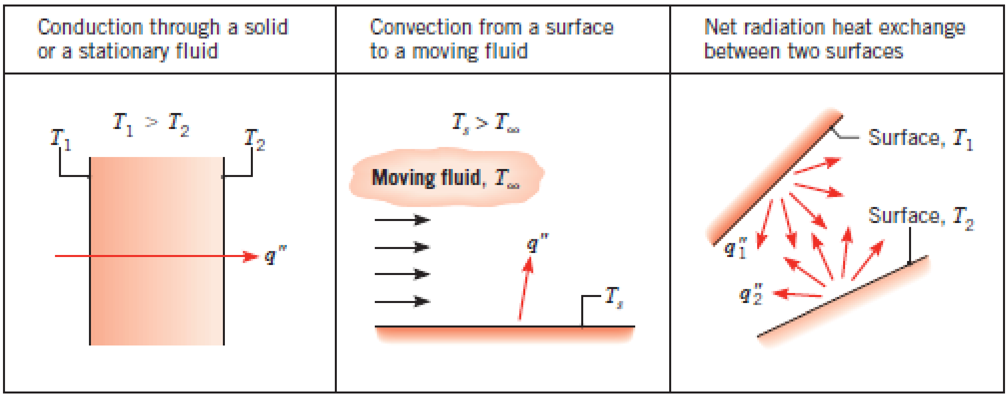


Figure 1 Conduction, convection and Radiation mode of heat transfer. Courtesy: Introduction to heat transfer Incropera Dewitt

FOURIER LAW OF HEAT CONDUCTION AND THERMAL CONDUCTIVITY

- Conduction mode of heat transfer is governed or governing law of conduction mode heat transfer is 'FOURIER LAW OF HEAT TRANSFER'
- As with every law it is an eternal truth, it cannot be proved but experimental evidences establish this law now let us see Fourier law

> Rate of heat conduction per unit area (heat flux) is directly proportional to temperature gradient.

- Mathematically

$$\frac{\dot{Q}}{A} \propto \frac{dT}{dx}$$

$$q = \frac{\dot{Q}}{A} = -k\frac{dT}{dx}$$ Heat conduction equation in heat flux format

$$\dot{Q} - kA\,\frac{dT}{dx}$$ Heat conduction equation in rate format

$$q = heat\ flux\ \frac{Watt}{m^2}$$

$\dot{Q} = Rate\ of\ heat\ transfer\ (Watt)$

$A = normal\ cross\ sectional\ area\ to\ heat\ transfer\ vector$ (m^2)

$\frac{dT}{dx} = Temperature\ gradient\ along\ direction\ of\ heat\ transfer$ (^0C/meter)

K = Thermal conductivity

> Find out unit of thermal conductivity from the principle of homogeneous ness of units.
>
> $$Watt = k\ \times meter^2 \times \frac{0_C}{meter}$$
>
> k = --------------------

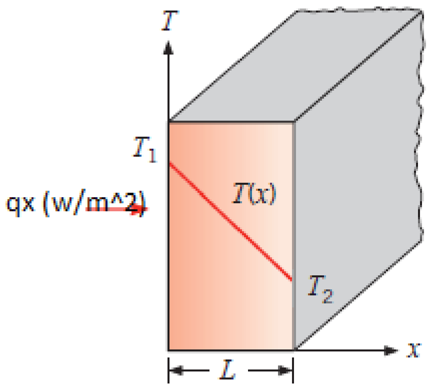


Figure 2 Representation of Fourier law of Heat transfer in one dimension along cartesian co ordinate system

Thermal conductivity a property of material defined as rate of heat transfer through a unit thickness of material per unit area per unit temperature difference

Solid	Liquid	Gas
Thermal conductivity decreases with rise in temperature	Thermal conductivity decreases with rise in temperature	Thermal conductivity increases with rise in temperature

Steady state heat conduction in cartesian coordinate system

- Consider a plane wall of thickness L it's left face is maintained at temperature T_1 and right face at x = L is maintained at T_2. The wall has constant thermal conductivity k.

$$\frac{\dot{Q}}{A} = -k\frac{dT}{dx}$$

$$\frac{\dot{Q}}{A}dx = -kdT \quad \textit{Variable separation method}$$

$$\frac{\dot{Q}}{A}\int_0^L dx = -k\int_{T_1}^{T_2} dT \quad \textit{Integrating}$$

$$\frac{\dot{Q}}{A}L = -k(T_2 - T_1)$$

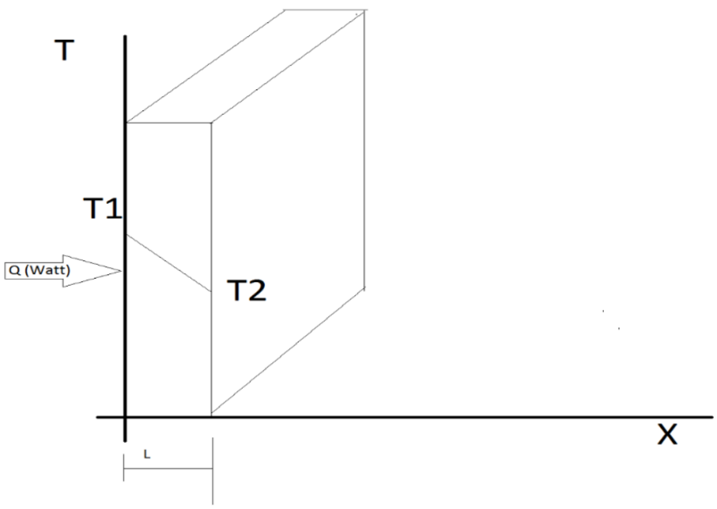
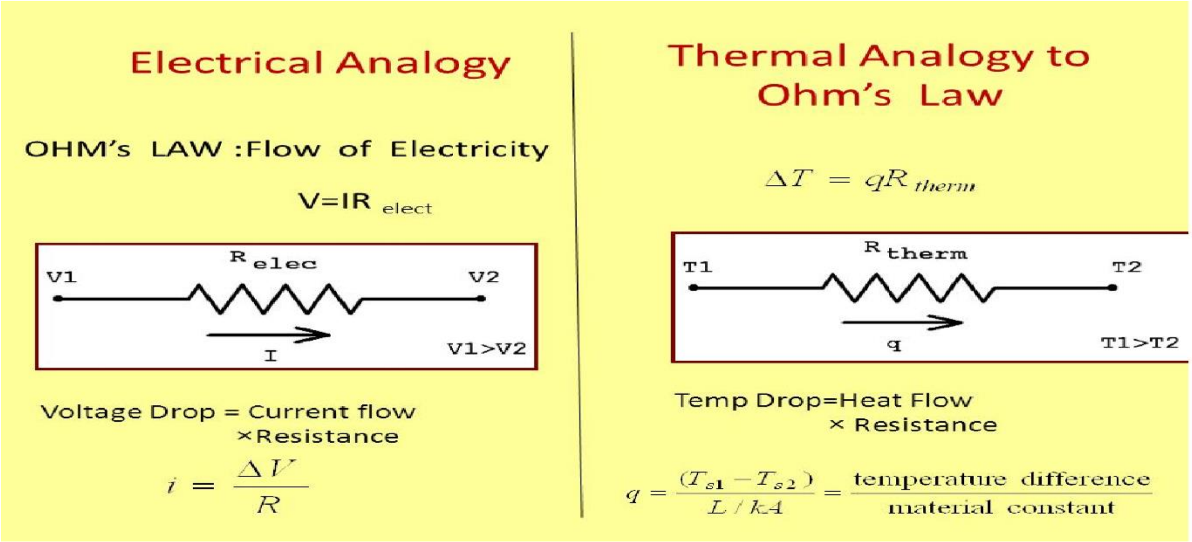


Figure 3, 1 - dimensonal steady state constant thermal conductivity with no internal heat generation in an isotropic material in cartesian co ordinate system



Heat transfer through cartesian wall in one dimenson can be calculated as

$$\dot{Q} = kA\frac{T_1 - T_2}{L}$$

Where $\dot{Q} = Rate\ of\ heat\ transfer\ \approx Electric\ current$

T_1- T_2= Drop in temperature ≈ Voltage difference

$$\frac{L}{kA} = Thermal\ resistance \approx electrical\ resistance$$

HOLLOW CYLINDER

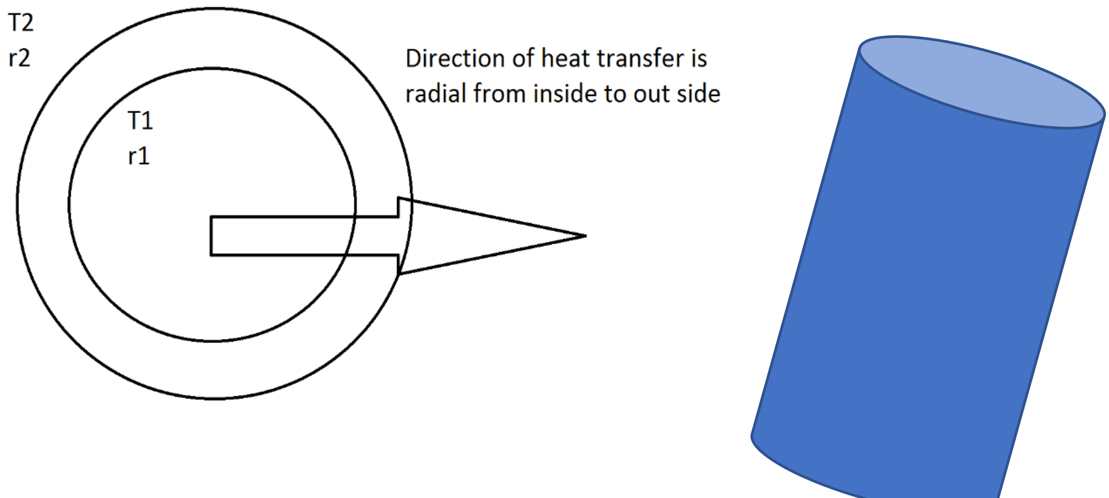


Figure 4 Radial heat transfer along the wall of a cylinder. end view of a cylinder is shown

$$\frac{\dot{Q}}{A} = -k\frac{dT}{dr}$$

Surface area of cylinder normal to heat transfer vector is $A = 2\pi rl$

Now separating the variables

$$\frac{\dot{Q}}{A}dr = -kdT$$

$$\frac{\dot{Q}}{2\pi rL}dr = -kdT$$

$$\frac{\dot{Q}}{2\pi L}\int_{r_1}^{r_2}\frac{dr}{r} = -k\int_{T_1}^{T_2} dT$$

$$\frac{\dot{Q}}{2\pi L}\,ln\frac{r_2}{r_1} = -k(T_2 - T_1)$$

In thermal analogy format

$$\dot{Q} = \frac{2\pi lk[T_1 - T_2]}{ln\frac{r_2}{r_1}}$$

In this equation

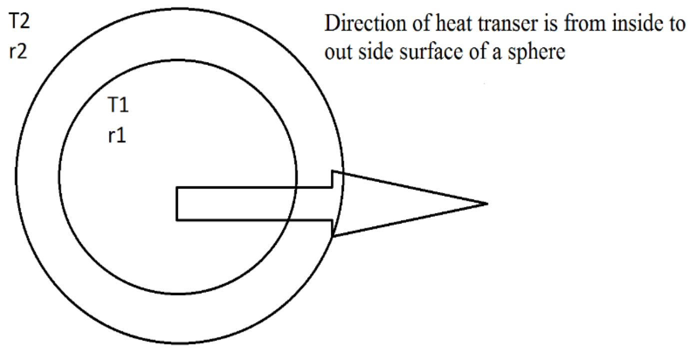
Identify

Rate of heat transfer---

Conduction resistance across cylindrical wall--

Temperature difference across the wall---

HOLLOW SPHERE



Consider a hollow sphere of inner radius r_1 maintained at temperature T_1 and outer radius r_2 maintained at temperature T_2

$$\frac{\dot{Q}}{A} = -k\frac{dT}{dr}$$

The normal surface area to heat transfer of a sphere $A_{sphere} = 4\pi r^2$

Now separating the variables

$$\frac{\dot{Q}}{A}dr = -kdT$$

$$\frac{\dot{Q}}{2\pi}\int_{r_1}^{r_2}\frac{dr}{r^2} = -k\int_{T_1}^{T_2} dT$$

$$\frac{\dot{Q}}{4\pi}\left[\frac{1}{r_1}-\frac{1}{r_2}\right] = -k(T_2 - T_1)$$

$$\dot{Q} = \frac{4\pi r_1 r_2 k(T_1 - T_2)}{r_2 - r_1}$$

In this equation

Identify

Rate of heat transfer---

Conduction resistance across cylindrical wall---

Temperature difference across the wall---

ASSIGNMENT

1. The wall of a furnace is constructed from 15 cm thick fire brick having a constant thermal conductivity of 1.7 W/mK. Two sides of wall are maintained at 1400 K and 1150 K respectively. What is the rate of heat loss through the wall of 50 cm × 3 m on a side?
2. Consider a furnace wall (k = 1 W/m^{0}C) with the inside surface is at 1000^{0}C and the outside surface is at 400^{0}C. The heat flow through wall is not exceeding 2000 W/m^2.Compute the minimum wall thickness

CONVECTION MODE OF HEAT TRANSFER & NEWTON'S LAW OF COOLING

- The convection mode of heat transfer is comprised of two mechanisms. Energy transfer due to random molecular motion (diffusion) and energy transferred by the bulk, or macroscopic, motion of the fluid.

- The term convection is used when referring to this cumulative transport (random motion of molecules and bulk motion of fluid chunk), and the term advection refers to transport due to bulk fluid motion.

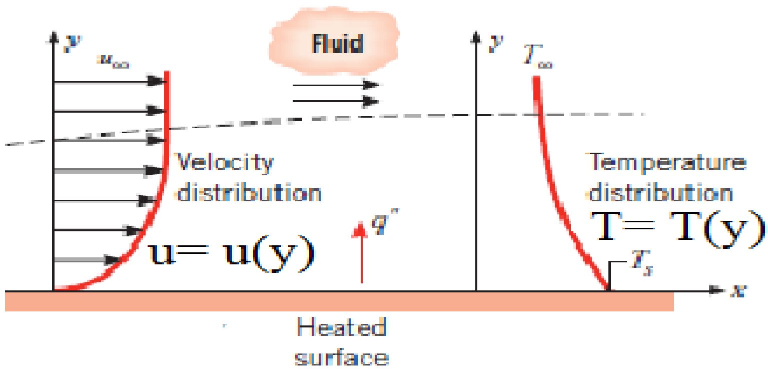
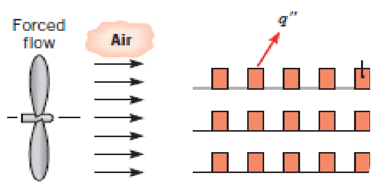


Figure 5 Velocity and thermal boundary layer development in convective mode of heat transfer

- We are especially interested in convection heat transfer, which occurs between a fluid in motion and a bounding surface when the two are at different temperatures. Consider fluid flow over the heated surface as shown in above figure. A consequence of the fluid–surface interaction is the development of a region in the fluid through which the velocity varies from zero at the surface to 'u_∞' free stream fluid temperature. This region of the fluid is known as the hydrodynamic, or velocity, boundary layer.

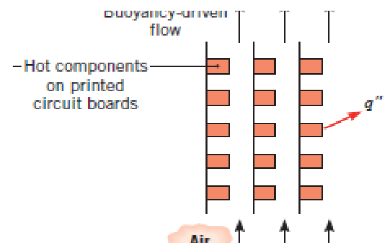
- Moreover, if the surface (T_s) and free stream fluid temperatures (T_∞) differ, there will be a region of the fluid through which the temperature varies from T_s at $y = 0$ to T_∞. This region, called the thermal boundary layer, may be smaller, larger, or the same size as that of velocity boundary layer.

classification of convection mode of heat transfer



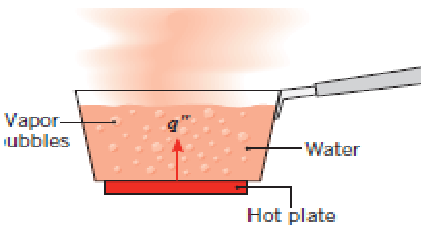
Forced convection

If the fluid motion is artificially induced by a pump, fan or blower that forces the fluid over a surface to flow.



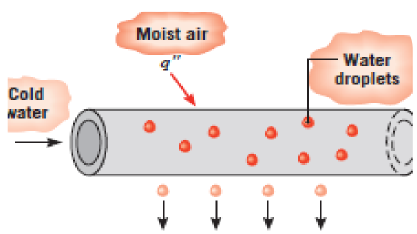
Natural convection

If the fluid motion is set up by buoyancy effects resulting from density difference caused by temperature difference in the fluid



Boiling

special case . Resulting due to latent heating of a pure substance. Fluid motion induced by vapour bubble generated at bottom of pan



Condensesation

special case . Resulting due to latent cooling of a pure substance. Fluid motion induced condensesation of water vapour at the outer surface of a cold pipe line

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- Convection mode of heat transfer is governed by Newton's law of cooling

$$\frac{\dot{Q}}{A}(\frac{Watt}{m^2}) \propto (T_s - T_\infty)$$

$$\frac{\dot{Q}}{A}\left(\frac{Watt}{m^2}\right) = h[T_s - T_\infty]$$

T_s = Surface temperature ^{0}C
T_∞ = Free stream fluid temperature
h = Constant of proportionality, convective heat transfer co efficient (Watt/m^2. ^{0}C)

RADIATION MODE OF HEAT TRANSFER

- When energy propagates in the form of electromagnetic waves from a high temperature region to a low temperature region, in the form of energy transfer is referred as thermal radiation.
- Radiation mode of heat transfer is governed by Stefan Boltzmann law

$$\frac{\dot{Q}}{A} \propto [T_s{}^4]$$

$$\frac{\dot{Q}}{A} = \sigma[T_s{}^4]$$

T_s = Absolute surface temperature K
$\sigma = Constant\ of\ proportionality\ called\ as\ Stefan\ Boltzman\ Constant$
Value of $\sigma = 5.67 \times 10^{-8} \left[\frac{Watt}{m^2K^4}\right]$
The heat flux emitted by a real surface is less than that of a black surface is given by

$$\frac{\dot{Q}}{A} = \sigma\epsilon[T_s^4]$$

$\epsilon = radiative\ surface\ property\ alled\ as\ emmissivity$

Net radiation heat transfer between a real surface and it's surrounding is

$$\frac{\dot{Q}}{A} = \sigma\epsilon[T_s^4 - T_\infty^4]$$

Kirchoff's Law

- All bodies radiate energy in the form of photons. When these photons reach another surface, they may either be absorbed, reflected or transmitted. The behaviour of a surface with incident radiation is described by the following quantities:
- absorptivity (α) is the fraction of incident radiation absorbed
- reflectivity (ρ) is the fraction of incident radiation reflected
- transmissivity (τ) is the fraction of incident radiation transmitted.

- From the principle of energy conservation

$\alpha + \rho + \tau = 1$

For opaque objects τ = 0
Hence for any opaque objects $\alpha + \rho = 1$

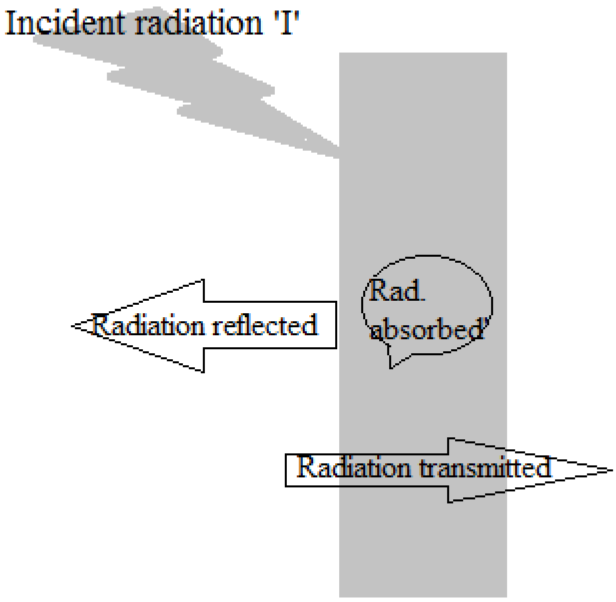


Figure 6 Absorptivity reflectivity and transmittivity of a body

- Heat flux emitted by a real surface is less than heat flux emitted by a black body. This is quantified by introducing emissivity ϵ.
- $\epsilon = \frac{E}{E_b}$
- $\epsilon = 1\ for\ black\ bodies$
- $0 < \epsilon < 1\ for\ real\ bodies$

- Consider a small real body in thermal equilibrium with its surrounding blackbody cavity i.e., $T_{body} = T_{cavity}$.
- The power emitted per unit area of the blackbody (cavity) is E_b
- Power absorbed by real body per unit area is given by $\propto E_b$
- The power emitted per unit area of the real body is equal to $E = \epsilon E_b$
- Now in due course of time when thermal equilibrium is established between black cavity and real body both will at same temperature

  $\in E_b = \alpha E_b$

  or

  $\epsilon \sigma T^4 = \alpha \sigma T^4$

  So it is obvious that $\epsilon = \alpha$

  Kirchhoff's law of radiation $\epsilon = \alpha$

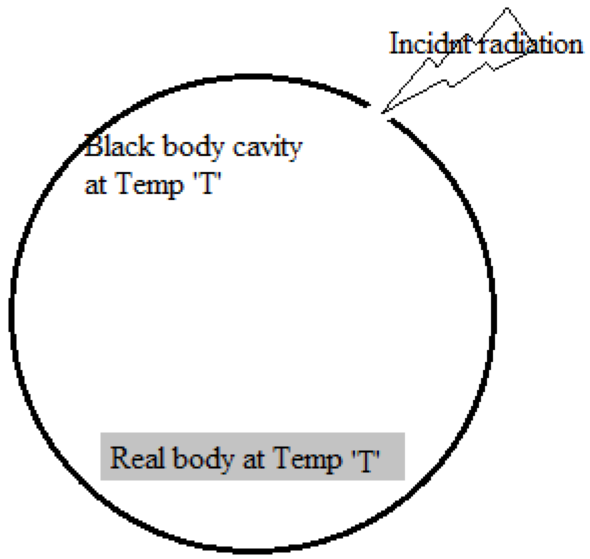
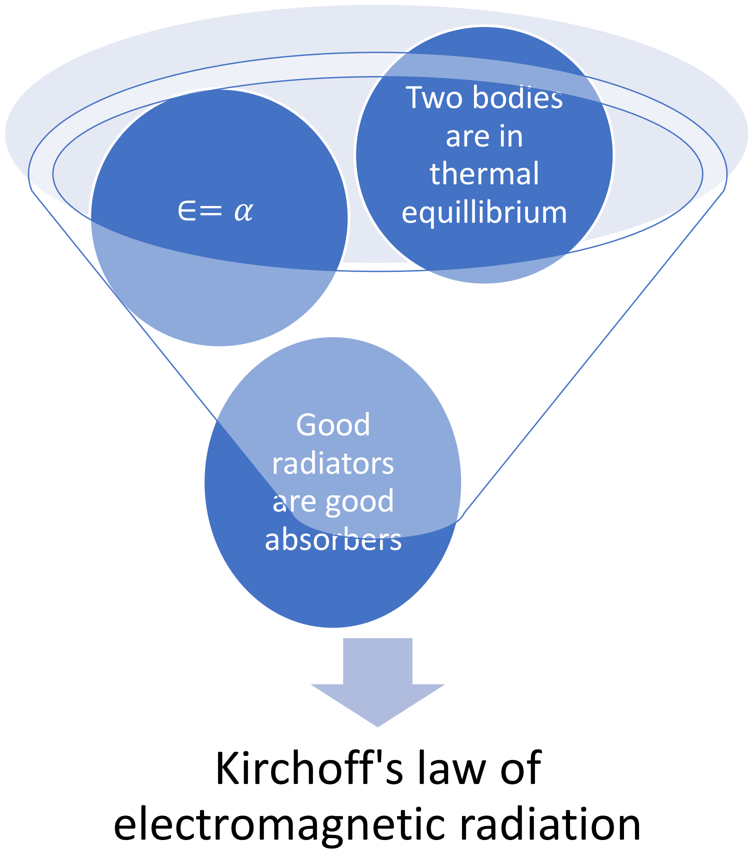


Figure 7 Black body radiation



Here I would like to share an an interesting research work on Kirchoff law You may read it to satisfy your quest to knowledge. However it is not included in your curriculum

https://vixra.org/pdf/1708.0053v1.pdf

ASSIGNMENT

1. A black surface is positioned in a vacuum container so that it absorbs incident solar radiant energy at the rate of 950 Watt/ m^2. If the surface conducts no heat to surrounding, determine it's equilibrium temperature.

2. A black body at 30^0C is heated to 100^0C. Calculate increase in emissive power.

3. The surface temperature of a central heating radiator is 60^0C. What is the net black body radiation heat transfer between radiator and surroundings at 20^0C.

4. Determine convection heat transfer rate over a surface of 1m2 if the surface at 100^0C is exposed to a fluid at 400C with convection co efficient 25 Watt/m^2K.