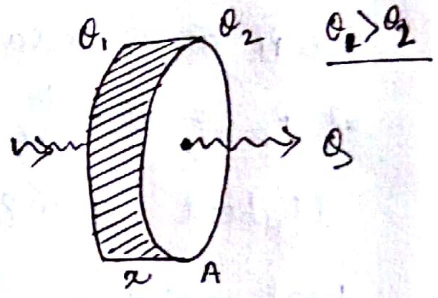
Conduction

Transmission of Heat : CONDUCTION, CONVECTION, RADIATION

In conduction, heat is transmitted from one point to other through the substance without actual motion of particles. Air or vacuum is poor conductor of heat, hence woolen fabric keeps us warm or thermos flask keeps thing isolated. In convection, heat is transmitted by the actual motion of particles. Hot water circulation in heated kettle. Heat radiation is transmitted directly without any intervening medium. Like sun radiation into earth by EM spectrum.

Coefficient of Thermal Conductivity



If we have a plane slab of area A, thickness x having temperature θ_1 & θ_2 at its two faces then if Q amount of heat is transmitted in time t, then,

$$Q \propto A$$
$$\propto (\theta_1 - \theta_2)$$
$$\propto 1/x$$
$$\propto t$$

$$\therefore \boxed{Q = \frac{KA(\theta_1-\theta_2)t}{x}}$$

K = coeff.^{n} of thermal conductivity

$$\therefore \underset{\text{heat current}}{q} = \frac{Q}{t} = \frac{KA(\theta_1-\theta_2)}{x} = \frac{\theta_1-\theta_2}{x/KA} = \frac{\theta_1-\theta_2}{\underset{\text{thermal resistance}}{R_{Th}}}.$$

This equation is similar to Ohm's law $I = \frac{V}{R}$, redefined in terms of thermal resistance & heat current. We know $R = \rho\frac{l}{A} = \frac{l}{\sigma A}$ where $\sigma = \frac{1}{\rho}$ is the electrical conductivity. Comparing with $R_{Th} = \frac{x}{KA}$ we can define the proportionality constant as coeff.^{n} of thermal conductivity

Dimension of $[Q] = [ML^2T^{-2}]$, $[x] = [L]$, $[A] = [L^2]$, $[\theta] = [\theta]$,

$[t] = [T]$

$\therefore [K] = [MLT^{-3}\theta^{-1}]$

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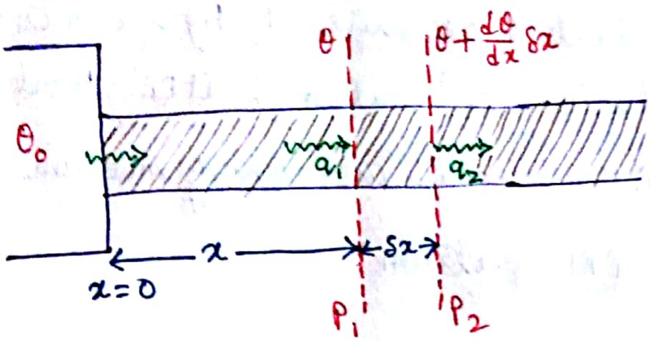
Thermal diffusivity is defined as the ratio of thermal conductivity to thermal capacity per unit volume. If ρ = density & S = specific heat then $h = \dfrac{K}{\frac{mS}{V}} = \dfrac{K}{\rho S}$ = "Thermometric conductivity"

Rectilinear Propagation of heat along a bar



Consider a bar of uniform area of cross-section A contact with an oven at temperature θ_0 at $x=0$. If θ is the excess temperature above the surroundings of the bar at P_1 at a distance x from the point of contact, then excess temperature at $P_2 = \theta + \dfrac{d\theta}{dx}\delta x$.

If heat flowing through P_1 in one second $q_1 = -KA\dfrac{d\theta}{dx}$ & heat flowing through P_2 in one second $q_2 = -KA\dfrac{d}{dx}\left(\theta + \dfrac{d\theta}{dx}\delta x\right)$

$\therefore$ Heat gained per second by the rod between P_1 & P_2

$$q = q_1 - q_2 = -KA\frac{d\theta}{dx} + KA\frac{d}{dx}\left(\theta + \frac{d\theta}{dx}\delta x\right)$$

$$= KA\frac{d^2\theta}{dx^2}\delta x$$

This amount of heat is used in two ways before steady state is reached. (1) A part will increase the temperature, (2) Rest part is lost due to radiation from the exposed surface of the slab.

If rate of rise of temperature is $\dfrac{d\theta}{dt}$ then heat used per second $= \underbrace{(A\delta x)\rho}_{\text{mass}} \times \underbrace{S}_{\text{specific heat}} \times \dfrac{d\theta}{dt}$ & heat lost per second due to radiation $= Ep\,\delta x\,\theta$ where E = emissive power of surface, p = perimeter & θ = average excess of temperature within P_1 & P_2.

$$\therefore\ q = A\delta x\rho S\frac{d\theta}{dt} + Ep\,\delta x\,\theta = KA\frac{d^2\theta}{dx^2}\delta x$$

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$$\boxed{\frac{K}{\rho s}\frac{d^2\theta}{dx^2} = \frac{d\theta}{dt} + \frac{PE}{A\rho s}\theta}$$ Fourier's differential equation

Special Cases 1: when heat lost by radiation is negligible:

When rod is covered by insulating materials, heat lost $E P \delta x \theta = 0$ & total heat gained by rod is to raise the temperature, using

$$\frac{K}{\rho s}\frac{d^2\theta}{dx^2} = \frac{d\theta}{dt} \quad \text{or} \quad h\frac{d^2\theta}{dx^2} = \frac{d\theta}{dt}$$

Special Cases 2: after the steady state is reached:

$$\frac{d\theta}{dt} = 0 \quad \text{and} \quad \frac{d^2\theta}{dx^2} = \frac{PE}{KA}\theta = \mu^2\theta$$

This is a second order homogeneous linear differential equation

If $\theta = e^{mx}$ is the trial solution then $m^2 = \mu^2$ or $m = \pm\mu$

$$\therefore \quad \theta = \underbrace{A_1 e^{\mu x} + A_2 e^{-\mu x}}_{\text{Boundary conditions}}$$

If the bar is sufficiently long, we can assume that under steady state no heat is lost from free end of the bar, as whole of the heat is lost from ~~free end~~ sides as radiation & free end will be at the temperature of the surroundings.

(a) when bar is of infinite length:

Boundary condition, $x = 0, \ \theta = \theta_0$ (Dirichlet B.C.)

$x = \infty, \ \theta = 0$

we see that $\theta = A_1 e^{\infty}$ can be true only if $A_1 = 0$. and

$\theta_0 = A_2$. $\therefore$ $\boxed{\theta = \theta_0 e^{-\mu x}}$

Thus after steady state is reached, temperature is exponentially distributed. This is useful in Ingen-Hausz experiment.

(b) When bar is of finite length: $x = 0, \ \theta = \theta_0$

$x = L, \ \frac{d\theta}{dx} = 0$ (Neumann B.C.)

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In this case $A_1 = \frac{\theta_0}{1+e^{2\mu L}}$, $A_2 = \frac{\theta_0}{1+e^{-2\mu L}}$

$\therefore$ Solution $\boxed{\theta = \theta_0\left[\frac{e^{\mu x}}{1+e^{2\mu L}} + \frac{e^{-\mu x}}{1+e^{-2\mu L}}\right]}$

Special Case I at steady state Ideal case when there is no loss of heat by radiation i.e. rod is thermally lagged & in steady state

$$h\frac{d^2\theta}{dx^2} = \frac{d\theta}{dt} = 0 \quad \text{or} \quad \frac{d^2\theta}{dx^2} = 0 \quad (\text{as } h \neq 0)$$ [Laplace equation in electrostatics]

Solving $\frac{d}{dx}\left(\frac{d\theta}{dx}\right) = 0$ or $\frac{d\theta}{dx}$ = constant = A

or $\theta = Ax + B$.

Find A & B using B.C. that $x = 0$, $\theta = \theta_0$

$x = l$, $\theta = \theta_m$ (say)

at unknown distance l, the temperature is θ_m.

$\theta_0 = B$. and then $\theta_m = Al + \theta_0$ or $A = \frac{\theta_m - \theta_0}{l}$

$\therefore \boxed{\theta = \theta_0 - \frac{\theta_0 - \theta_m}{l}x}$

"The decrement is linear, as solution of Laplace equation is always a straight line."

In steady state length upto which wax melts in wax coated bar

from $\theta = \theta_0 e^{-\mu x}$, $\ln\frac{\theta}{\theta_0} = -\mu x$ we see that if we have number of bars with conductivities $K_1, K_2, K_3, \ldots$ etc & wax melts upto length $l_1, l_2, l_3, \ldots$ etc then at these length the temperature would be melting point of wax (say θ_m).

$$\therefore \ln\frac{\theta_m}{\theta_0} = -\mu_1 l_1 = -\mu_2 l_2 = -\mu_3 l_3 = \cdots$$

$$\therefore \sqrt{\frac{PE}{K_1 A}}\, l_1 = \sqrt{\frac{PE}{K_2 A}}\, l_2 = \sqrt{\frac{PE}{K_3 A}}\, l_3 = \cdots$$

or $l/\sqrt{K}$ = constant $\Rightarrow l \propto \sqrt{K}$

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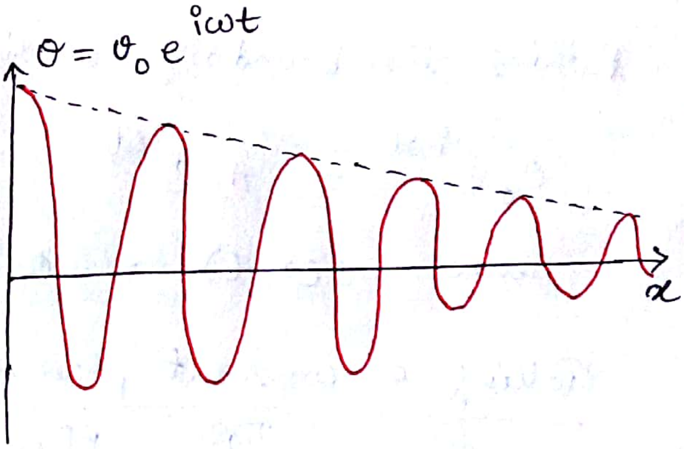
Hence in a steady state the length upto which the wax melts along a wax coated bar is proportional to the square root of the coefficient of thermal conductivity of the material.

Periodic flow of heat : Propagation of heat wave in an insulated rod with one end heated sinusoidally.



Consider a system of infinite length, well insulated (no loss due to radiation) whose one end is connected to an heat source from where heat is supplied not continuously but periodically. with θ_0 amplitude and ω being the angular frequency.

Using Fourier's equation $h\frac{d^2\theta}{dx^2} = \frac{d\theta}{dt} + \cancel{\frac{PE}{A\rho s}\theta}$ without radiation loss, the unidirectional heat equation is $h\frac{d^2\theta}{dx^2} = \frac{d\theta}{dt}$, $h = \frac{K}{\rho s}$ is the thermal diffusivity of the rod.

Let $\theta = u(x) + v(x,t)$ is a trial solution. then separating the variables, $\frac{d^2u}{dx^2} = 0$, $h\frac{d^2v}{dx^2} = \frac{dv}{dt}$

The solution of v-equation can be $v = F(x)e^{i\beta t}$

$\therefore hF''(x) = i\beta F(x)$ $\therefore$ $F''(x) = \frac{i\beta}{h}F(x) = \left(\sqrt{\frac{i\beta}{h}}\right)^2 F(x)$.

Taking the trial solution as $F(x) = Ae^{mx}$ we obtain,

$m^2 = \frac{i\beta}{h}$ or $m = \pm\sqrt{\frac{i\beta}{h}}$ $\therefore F(x) = A_1 e^{\sqrt{i\beta/h}\,x} + A_2 e^{-\sqrt{i\beta/h}\,x}$

As $x \to \infty$ yields $F(x) \to \infty$ (unphysical), so $A_1 = 0$.

$\therefore F(x) = A_2 e^{-\sqrt{\frac{i\beta}{h}}x}$

Now $(1+i)^2 = 2i$ or $i = \frac{1}{2}(1+i)^2$ or $\sqrt{i} = \pm\frac{1}{\sqrt{2}}(1+i)$

$\therefore F(x) = A_2 e^{-(1+i)\sqrt{\frac{\beta}{2h}}x} + A_3 e^{(1+i)\sqrt{\frac{\beta}{2h}}x}$

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$$\therefore \; v = f(x)\, e^{i\beta t} = \left[A_2 e^{-\sqrt{\frac{\beta}{2h}}x} e^{i(\beta t - \sqrt{\frac{\beta}{2h}}x)} + A_3 e^{\sqrt{\frac{\beta}{2h}}x} e^{i(\beta t + \sqrt{\frac{\beta}{2h}}x)} \right]$$

Here also, as $x \to \infty$, $v \to \infty$ (unphysical), hence $A_3 = 0$.

$$\therefore \; v(x,t) = A_2 e^{-\sqrt{\frac{\beta}{2h}}x} e^{i(\beta t - \sqrt{\frac{\beta}{2h}}x)}$$

Putting the boundary condition for $\theta = \theta_0 e^{i\omega t}$ at $x = 0$, we see

$$\theta_0 e^{i\omega t} = A_2 e^{i\beta t} \qquad \therefore \; A_2 = \theta_0, \; \beta = \omega.$$

Hence $$v(x,t) = \theta_0 e^{-\sqrt{\frac{\omega}{2h}}x} e^{i(\omega t - \sqrt{\frac{\omega}{2h}}x)}$$

Taking a constant phase factor ϕ from the solution of u, we have

$$\boxed{\theta = \theta_0 e^{-\sqrt{\frac{\omega}{2h}}x} e^{i[\omega t - \sqrt{\frac{\omega}{2h}}x - \phi]}}$$

This represents a progressive wave traveling with velocity

$$V = \frac{\omega}{K} = \frac{\omega}{\sqrt{\frac{\omega}{2h}}} = \sqrt{2\omega h} = \sqrt{\frac{2\omega K}{\rho S}} = \sqrt{\frac{2K}{\rho S}\frac{2\pi}{T}} = \sqrt{\frac{4\pi K}{T\rho S}}$$

damping factor $= \sqrt{\frac{\omega}{2h}}$

As $\frac{\lambda}{T} = v = \sqrt{\frac{4\pi K}{T\rho S}}$ or $K = \frac{\lambda^2 \rho S}{4\pi T}$

CW In a periodic flow of heat along an iron bar, the periodic time is 4 minute. If the temperature travels maximum 6 cm in 1 minute, calculate the thermal conductivity of iron. Density of iron $= 7.8 \; gm/cm^3$, specific heat of iron $= 0.11$ cal/gm °C.

$$v = \sqrt{2\omega h} = \sqrt{\frac{4\pi K}{T\rho S}} \quad \text{or} \quad v^2 = \frac{4\pi K}{T\rho S}$$

Here $v = 6$ cm/min $= 0.1$ cm/sec, $T = 4$ min $= 4 \times 60 = 240$ sec

$S = 0.11$ cal/gm °C, $\rho = 7.8 \; gm/cm^3$

$$\therefore K = \frac{v^2 T \rho S}{4\pi} = \frac{0.1^2 \times 240 \times 7.8 \times 0.11}{4 \times 3.14} = 0.1639 \; cal\, cm^{-1} sec^{-1} \,°C^{-1}$$

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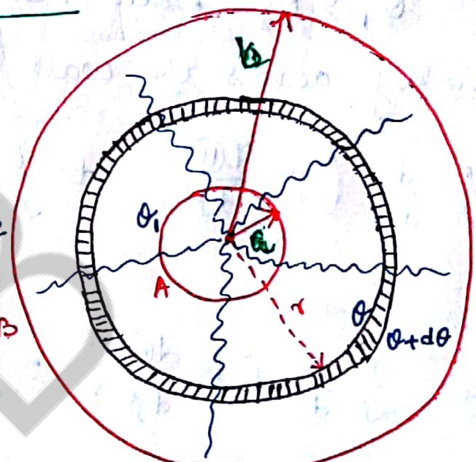
Heat flow in three dimensions

We have learned Fourier's law in one dimension,

$h \frac{d^2\theta}{dx^2} = \frac{d\theta}{dt} + \mu^2 h\theta$. In three dimensions, we have

$h\nabla^2\theta = \frac{d\theta}{dt} + \mu^2 h\theta$. In steady state, $\frac{d\theta}{dt} = 0$ and without radiation loss, $\mu^2 = 0$ yields $\boxed{\nabla^2\theta = 0}$ This is called "Laplace equation" of heat flow. Compare with Electrostatics, Laplace equation.

ⓐ Spherical shell Method (Radial flow)



Consider a spherical shell of inner radius a and outer radius b. Let θ_1 & θ_2 are the temperature at inside & outside the sphere. We want to find out temperature at $a<r<b$.

In ~~sphere~~ spherical polar coordinates, Laplace eqn. is

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial \Theta}{\partial r}\right) + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial\Theta}{\partial\theta}\right)^{\nearrow 0} + \frac{1}{r^2\sin^2\theta}\frac{\partial^2\Theta}{\partial\phi^2}^{\nearrow 0} = 0$$

$[\text{as } \Theta \neq \Theta(\theta,\phi)]$

or $\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial\Theta}{\partial r}\right) = 0$

or $r^2\frac{d\Theta}{dr} = \text{constant} = C_1$ (say)

or $d\Theta = \frac{C_1}{r^2}dr$ or $\Theta = -\frac{C_1}{r} + C_2$

Now we use Dirichlet Boundary condition $\Theta = \theta_1$ at $r=a$
$\Theta = \theta_2$ at $r=b$.

$\therefore \theta_1 = -\frac{C_1}{a} + C_2$

$\theta_2 = -\frac{C_1}{b} + C_2$

or $(\theta_1 - \theta_2) = C_1\left(\frac{1}{b} - \frac{1}{a}\right)$

or $C_1 = \frac{ab(\theta_1-\theta_2)}{a-b}$

$\therefore C_2 = \theta_1 + \frac{C_1}{a} = \theta_1 + \frac{(\theta_1-\theta_2)b}{a-b} = \frac{a\theta_1 - b\theta_2}{a-b}$.

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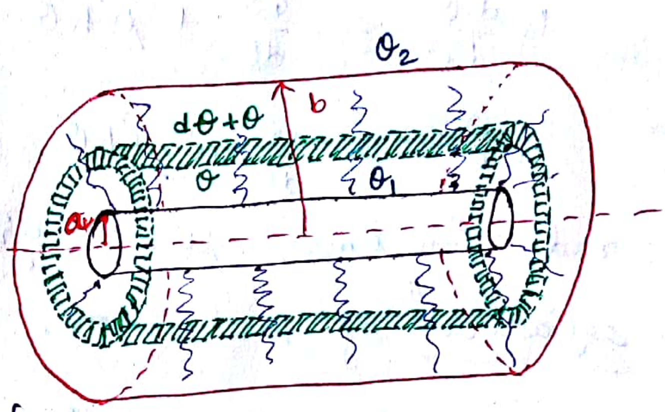
∴ The temperature at any distance r is

$$\Theta = \left[\frac{ab(\theta_1-\theta_2)}{b-a}\right]\frac{1}{r} + \frac{a\theta_1 - b\theta_2}{a-b}$$

(b) Cylindrical flow of heat



Consider a cylindrical tube of length l, inner radius a & outer radius b with temperature of inner surface θ_1 & outer surface θ_2 with $\theta_1 > \theta_2$ where heat is conducted radially across the wall of the tube. ~~Hel~~ Laplace eqn becomes

$$\frac{1}{\rho}\frac{d}{d\rho}\left(\rho\frac{\partial\Theta}{\partial\rho}\right) + \cancel{\frac{1}{\rho^2}\frac{\partial^2\Theta}{\partial\theta^2}}^{0} + \cancel{\frac{\partial^2\Theta}{\partial\phi^2}}^{0} = 0$$

$$[\Theta \neq \Theta(\theta,\phi)]$$

or $\frac{1}{\rho}\frac{d}{d\rho}\left(\rho\frac{d\Theta}{d\rho}\right) = 0$ or $\rho\frac{d\Theta}{d\rho} = \text{constant} = c_1$

or $d\Theta = \frac{c_1}{\rho}d\rho$ or $\Theta = c_1 \ln\rho + c_2$

We use Dirichlet boundary condition, $\Theta = \theta_1$ at $\rho = a$
$\Theta = \theta_2$ at $\rho = b$.

∴ $\theta_1 = c_1 \ln a + c_2$
$\theta_2 = c_1 \ln b + c_2$

or $\theta_1 - \theta_2 = c_1 \ln a/b$.

or $c_1 = \frac{\theta_1-\theta_2}{\ln a/b}$.

∴ $c_2 = \theta_1 - c_1\ln a = \theta_1 - \frac{(\theta_1-\theta_2)}{\ln a/b}\ln a = \frac{\theta_1(\ln a - \ln b) - (\theta_1-\theta_2)\ln a}{\ln a/b}$

$= \frac{\theta_2\ln a - \theta_1 \ln b}{\ln a/b}$. So the temperature at any distance

r is, $\Theta = \frac{\theta_1-\theta_2}{\ln a/b}\ln\rho + \frac{\theta_2\ln a - \theta_1\ln b}{\ln a/b}$

Using Fourier's law at unit time, $Q = K\, 2\pi r l \frac{d\theta}{dr}$

or $Q\int_a^b \frac{dr}{r} = 2\pi K l \int_{\theta_1}^{\theta_2} d\theta = 2\pi K l(\theta_2 - \theta_1)$.

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∴ $Q_2 \ln\frac{b}{a} = 2\pi K l(\theta_2-\theta_1)$ ∴ $Q_2 = \frac{2\pi K l(\theta_1-\theta_2)}{\ln a/b}$

or $K = \frac{Q_2 \ln a/b}{2\pi l(\theta_1-\theta_2)}$

Wiedemann-Franz law The law states that ratio of thermal and electrical conductivities for all metals is directly proportion to the absolute temperature of the body.

$$\frac{K}{\sigma} \propto T \quad \text{or} \quad \frac{K}{\sigma T} = \text{constant} = 2\sqrt{\frac{6}{\pi}}\,\frac{K_B^2}{e^2} = L \text{ (Loretz number)}$$

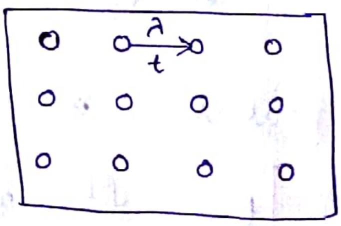
Physically this means that substances which are good conductor of heat are also good conductor of electricity.

Drude's theory of electrical conduction

Drude in 1900 introduced the concept of free electron gas model of metals, & obtained the electric conductivity of the metal. All metals (conductors) contain a huge number of nearly free electrons that behave as gas atoms in Kinetic theory. If m is mass of electron & v is velocity at temperature T,

$$\frac{1}{2}mv_{rms}^2 = \frac{3}{2}K_BT \quad \text{or} \quad v_{rms} = \sqrt{\frac{3K_BT}{m}}$$

If we apply an electric field E & then electron will experience a force eE and accelarate with $\frac{eE}{m}$. Now as the electron moves to hit an atom or ion, if λ is the mean interatomic distance that is gone in time t then average drift velocity of the electron



is $v_d = \frac{eE}{2m}t = \frac{eE}{2m}\frac{\lambda}{v}$

∴ The current density $J = nev_d = \frac{ne^2\lambda}{2mv_{rms}}E = \sigma E$

and Thermal conductivity $K = \frac{1}{3}n\bar{c}\lambda\frac{dE}{dT}$ & for only translational energy case, $E = \frac{3}{2}K_BT$, $K = \frac{1}{3}n\bar{c}\lambda\frac{3}{2}K_B = \frac{1}{2}n\bar{c}\lambda K_B$

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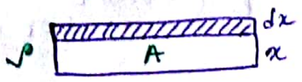
$$\therefore \frac{K}{\sigma} = \frac{\frac{1}{2} n\bar{c}\lambda k_B}{ne^2\lambda} \, 2m\sqrt{\frac{3k_BT}{m}}$$

$$= 2\sqrt{\frac{8k_BT}{\cancel{m}\pi}} \, \frac{\cancel{n}\cancel{\lambda}k_B}{2\cancel{n}e^2\cancel{\lambda}} \, \cancel{m}\sqrt{\frac{3k_BT}{\cancel{m}}} = 2\sqrt{\frac{6}{\pi}} \, \frac{k_B^2}{e^2} T.$$

$\therefore \frac{K}{\sigma T}$ = constant = Loretz number L.

Heat conduction through a slab of varying thickness



To form ice, 80 cals of heat are given out at 0°C when some thick ice layer has formed, heat given out has to conduct through this thickness. Let us find out the time required to increase the icelayer from x_1 to x_2. If at t, ice formed is x then within time dt, dx thickness of ice is formed, then the heat liberated is $Q = A\,dx\,\rho L$. This heat flows in dt from 0°C to outside temperature $-\theta$°C.

$$\therefore Q = \frac{KA[0-(-\theta)]dt}{x} = \frac{KA\theta}{x}dt$$

$$\therefore A\,dx\,\rho L = \frac{KA\theta}{x}dt \quad \text{or} \quad x\,dx = \frac{K\theta}{\rho L}dt$$

Integrating, $\frac{1}{2}x^2 = \frac{K\theta}{\rho L}t + c$

Now at $t=0$, $x = x_1$, $t = t_2$, $x = x_2$

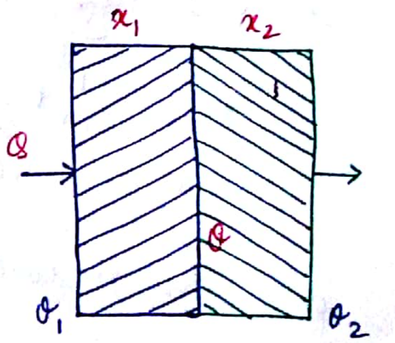
$$\therefore \frac{1}{2}x_1^2 = c \quad \& \quad \frac{1}{2}x_2^2 = \frac{K\theta}{\rho L}t_2 + \frac{1}{2}x_1^2$$

$$\text{or} \quad t_2 = \frac{\rho L}{2K\theta}(x_2^2 - x_1^2)$$

If at $t=0$, $x=0$ then time required to form a layer of thickness x is

$$\boxed{t = \frac{\rho L}{2K\theta}x^2}$$

Heat conduction through a composite slab



Consider a slab made of two materials of thickness x_1 and x_2 and conductivities K_1 and K_2. At steady state, heat enters at θ_1

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crossing interface at θ & leaves out of the second face θ_2.

$$Q = \frac{K_1 A(\theta_1 - \theta)}{x_1} = \frac{K_2 A(\theta - \theta_2)}{x_2}$$

$$\text{or } Q = \frac{A(\theta_1 - \theta)}{\frac{x_1}{K_1}} = \frac{A(\theta - \theta_2)}{\frac{x_2}{K_2}} = \frac{A(\theta_1 - \theta_2)}{\frac{x_1}{K_1} + \frac{x_2}{K_2}}$$

If the composite slab can be replaced by a single slab of thickness $x_1 + x_2$ such that it will conduct in unit time heat Q under temperature difference $\theta_1 - \theta_2$, then the equivalent conductivity be K., then

$$Q = \frac{KA(\theta_1 - \theta_2)}{x_1 + x_2} = \frac{A(\theta_1 - \theta_2)}{\frac{x_1}{K_1} + \frac{x_2}{K_2}} \quad \therefore \frac{x_1 + x_2}{K} = \frac{x_1}{K_1} + \frac{x_2}{K_2}$$

If we have $n \geq 2$ slabs then $\frac{x_1 + x_2 + x_3 + \cdots}{K} = \frac{x_1}{K_1} + \frac{x_2}{K_2} + \frac{x_3}{K_3} + \cdots$

$$\text{or } \sum_{i=1}^{N} x_i \frac{1}{K} = \sum_{i=1}^{N} \frac{x_i}{K_i} \quad \therefore \boxed{K = \frac{\sum_{i=1}^{N} x_i}{\sum_{i=1}^{N} \frac{x_i}{K_i}}}$$

HW ① One end of a metal rod is in contact with a source of heat at 100°C. In the steady state the temperature at a point 10 cm from the source is 60°C. Find the temperature at a point 20 cm from the source.

② Suppose 10 cm of ice has already formed on a pond so that the air outside is at −5°C. How long will it take for the next milimeter to form? Given for ice $L = 80$ Cal/gm, $\rho = 0.917$ gm/cc & $K = 0.005$ cgs unit.

③ A lake is covered with ice 2 cm thick. Temperature of air is −15°C. Find the rate of thickening of ice in cm/hour. For ice given $K = 0.004$ cgs unit, $\rho = 0.9$ gm/cc, $L = 80$ cal/gm.

④ Two equal bars of copper & aluminium are welded end to end and lagged. If the free ends of the copper & aluminium are maintained at 100°C and 0°C respectively. Find the temperature of welded surface K of Cu & Al are 0.92 and 0.5 cgs unit respectively.

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