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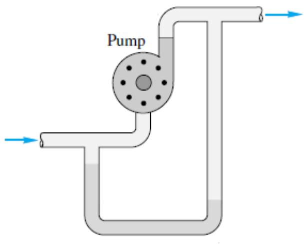
Mechanical Engineering (2)



Fayoum University

Faculty of Engineering
Mechanical Engineering Dept.

Lecture (9)

on

Heat Transfer Mechanisms

By

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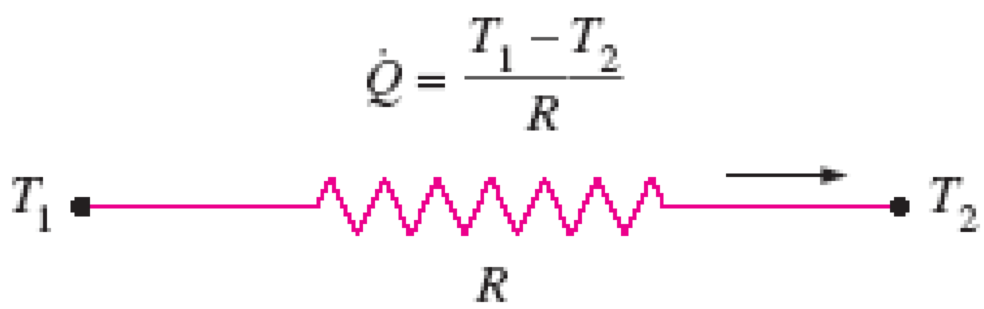
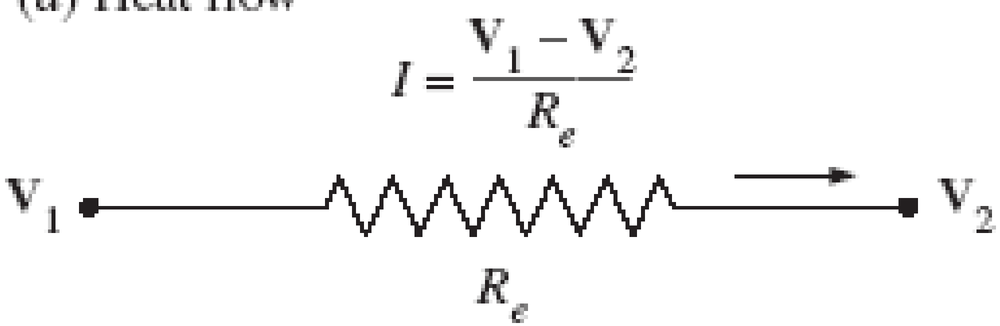
Mechanical Engineering Dept.
Faculty of Engineering
Fayoum University

2015 - 2016

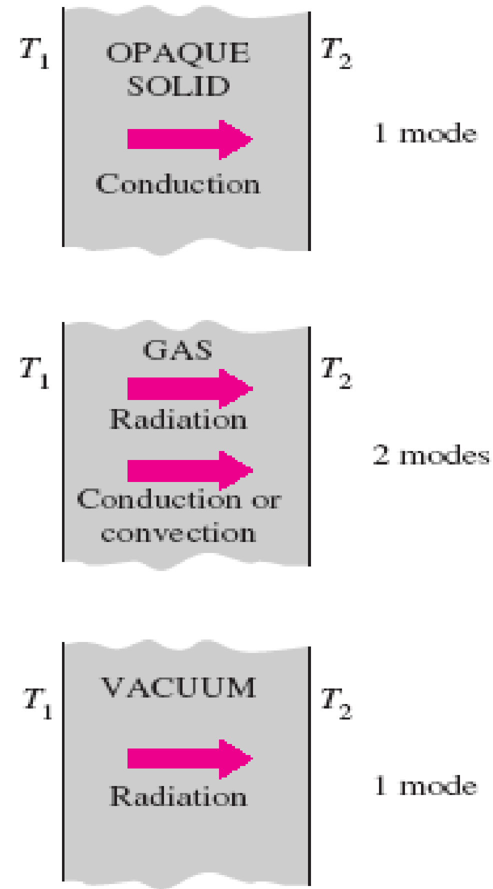
Heat Transfer Mechanisms



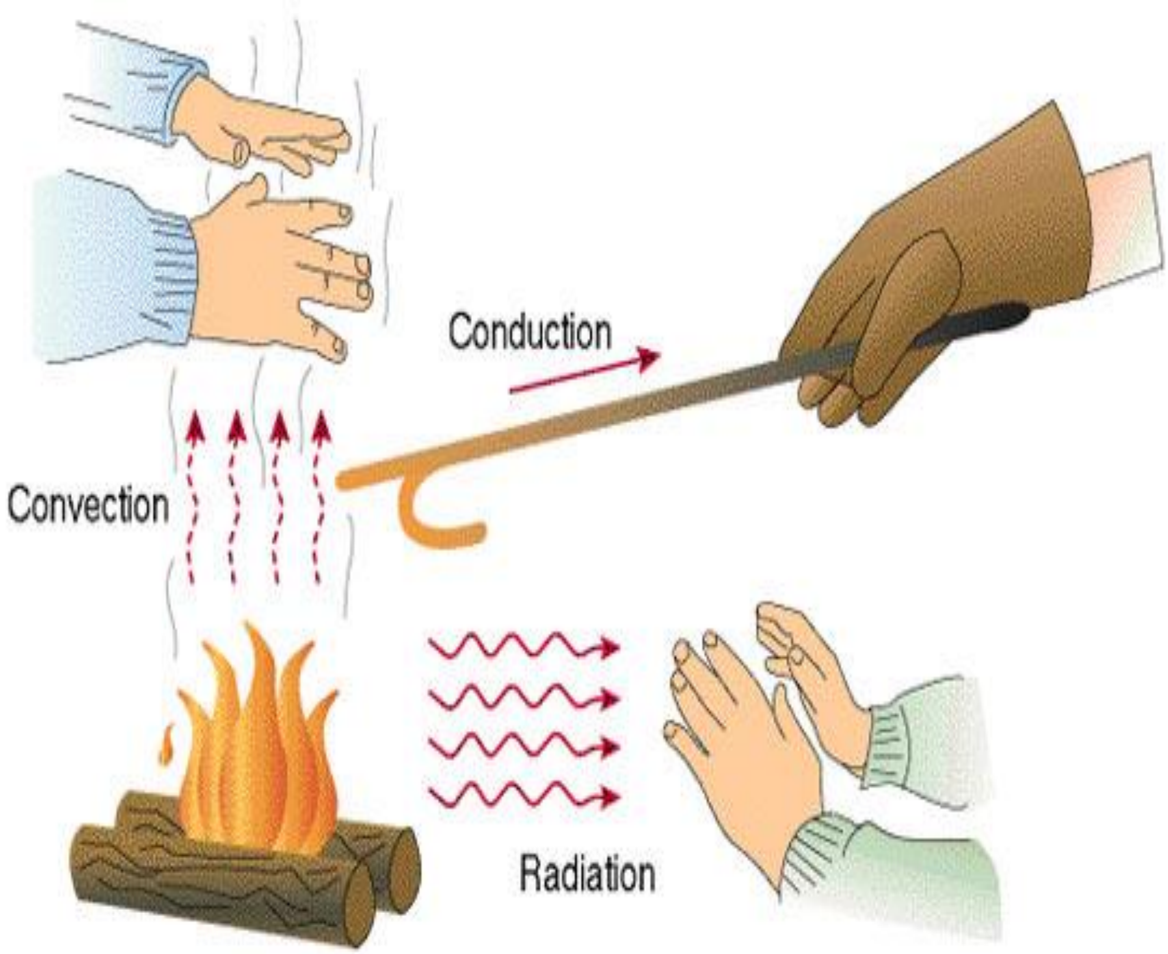
(*a*) Heat flow



(*b*) Electric current flow



Heat Transfer Mechanisms

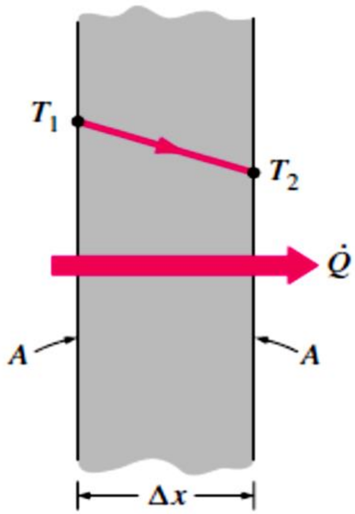


Heat Transfer Mechanisms - Conduction

$$Rate\ of\ heat\ conduction\ \alpha\ \frac{(Area)(Temperture\ difference)}{Tickness}$$

$$\dot{Q}_{cond} = kA\frac{T_1 - T_2}{\Delta x} = -kA\frac{\Delta T}{\Delta x}$$

where the constant of proportionality k is the thermal conductivity of the material, which is *a measure of the ability of a material to conduct heat.*



The thermal conductivities of some materials at room temperature

Material	k, W/m · °C*
Diamond	2300
Silver	429
Copper	401
Gold	317
Aluminum	237
Iron	80.2
Mercury (l)	8.54
Glass	0.78
Brick	0.72
Water (l)	0.613
Human skin	0.37
Wood (oak)	0.17
Helium (g)	0.152
Soft rubber	0.13
Glass fiber	0.043
Air (g)	0.026
Urethane, rigid foam	0.026

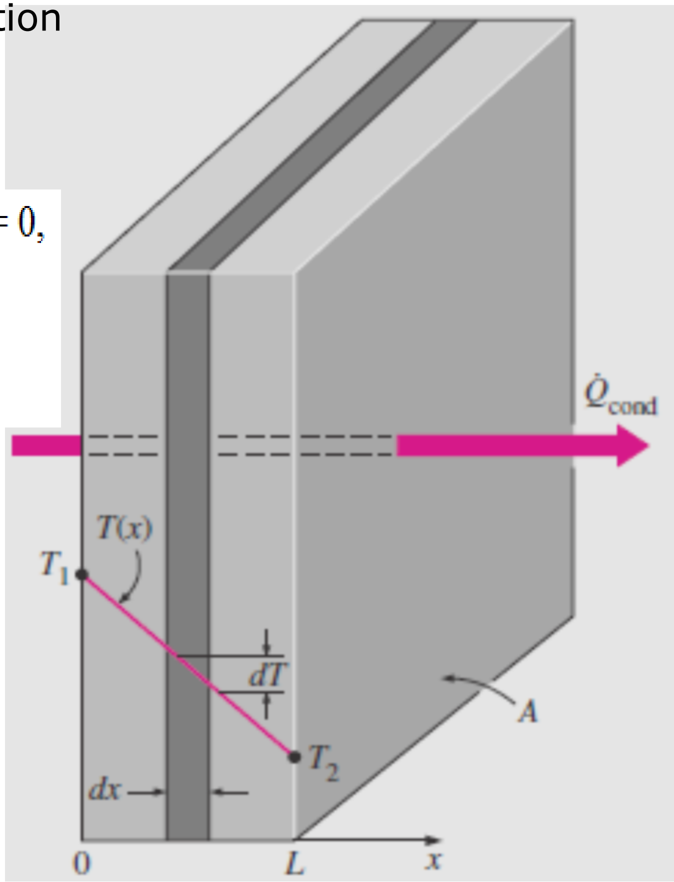
Heat Transfer Mechanisms - Conduction

To find the general form of one-dimensional heat transfer by conduction through plane wall and temperature distribution

$$\dot{Q}_{cond\,,wall} = -kA\frac{dT}{dx}$$

Separating the variables in the above equation and integrating from $x = 0$, where $T(0) = T_1$, to $x = L$, where $T(L) = T_2$, we get

$$\int_{x=0}^{L} \dot{Q}_{cond,wall}\,dx = \int_{T=T_1}^{T_2} kA\;dT$$



$$\boxed{\begin{aligned} \dot{Q}_{\text{plane wall}} &= k\,A\,\frac{T_1 - T_2}{L} \\ \dot{Q}_{\text{cylinder}} &= 2\pi k\,L\,\frac{T_1 - T_2}{\ln(r_2/r_1)} \\ \dot{Q}_{\text{sphere}} &= 4\pi k\,r_1 r_2\,\frac{T_1 - T_2}{r_2 - r_1} \end{aligned}}$$

For Plane wall

For Cylinder

For Sphere

Heat Transfer Mechanisms - Conduction

Thermal Diffusivity

Another material property that appears in the transient heat conduction analysis is the thermal diffusivity, which represents how fast heat diffuses through a material and is defined as

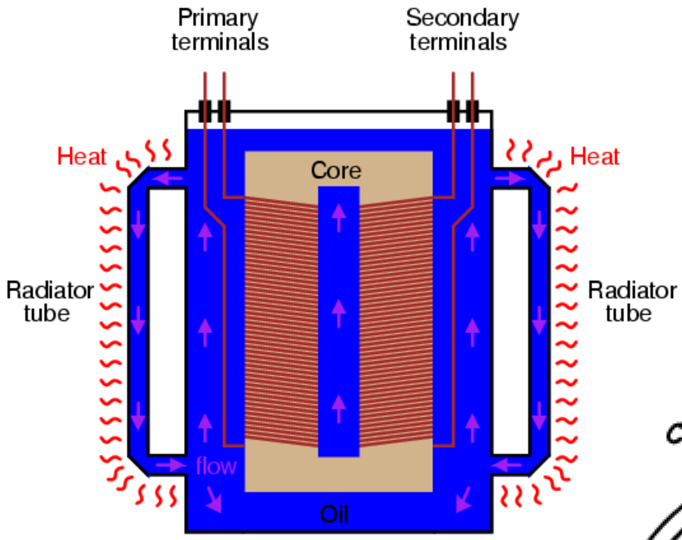
$$\alpha = \frac{\text{Heat conducted}}{\text{Heat stored}} = \frac{k}{\rho C_p} \qquad (\text{m}^2/\text{s})$$

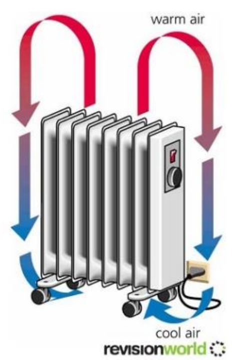
Note that the thermal conductivity k represents how well a material conducts heat, and the heat capacity ρC_p represents how much energy a material stores per unit volume. Therefore, the thermal diffusivity of a material can be viewed as the ratio of the *heat conducted* through the material to the *heat stored* per unit volume.

Heat Transfer Mechanisms - Convection

- Convection Mechanism
  - Natural or Free Convection
  - Forced Convection
    - External Forced Convection
    - Internal Forced Convection

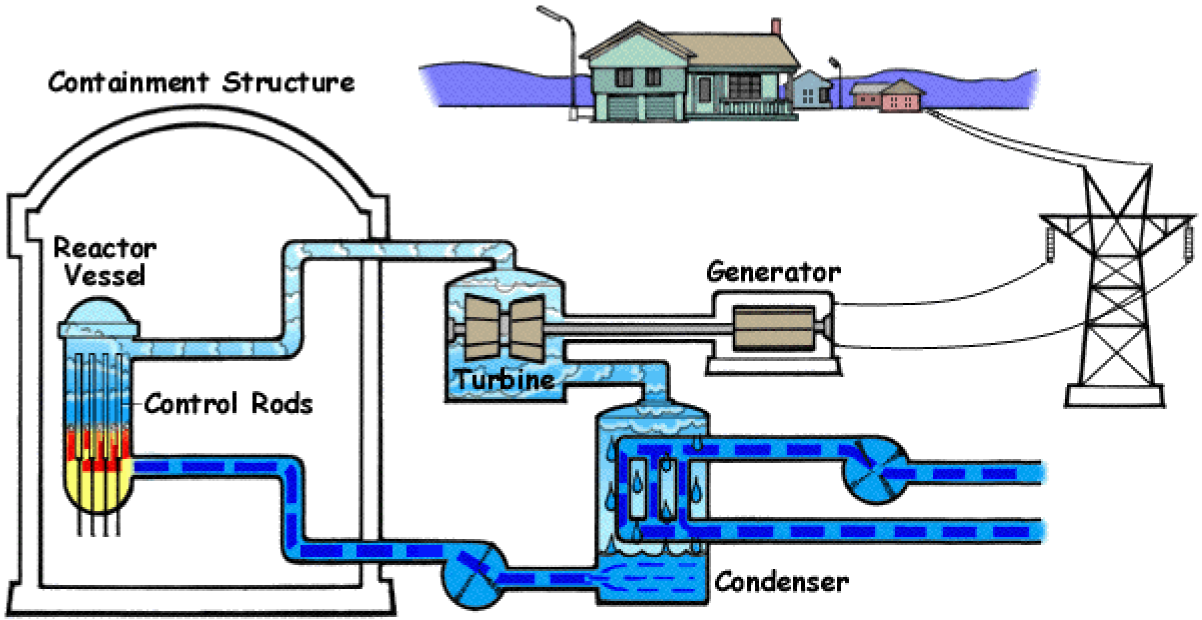
Heat Transfer Mechanisms - Convection





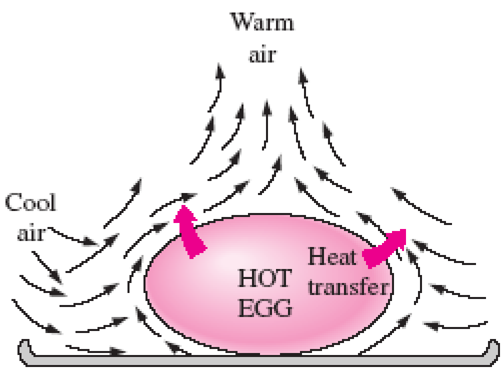
Natural or Free Convection

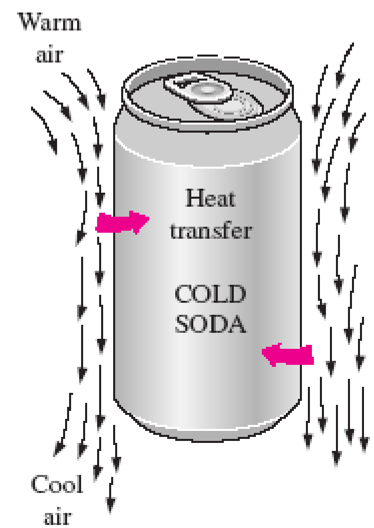
Forced Convection

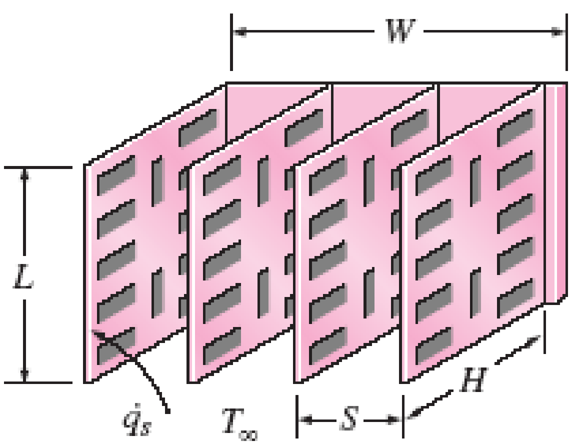


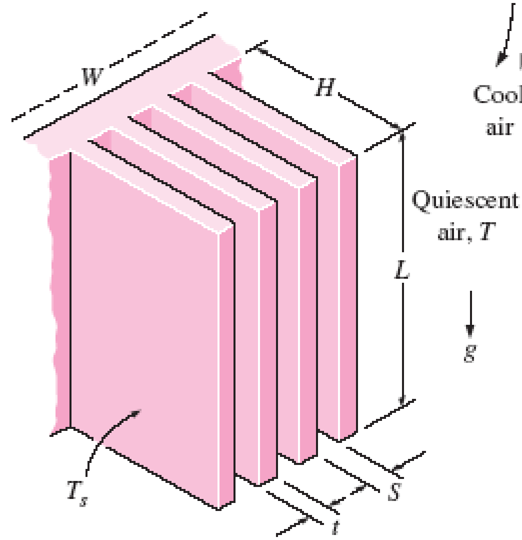
Heat Transfer Mechanisms - Convection

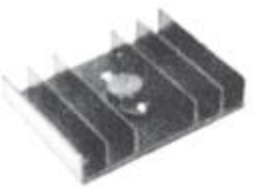
Natural or Free Convection

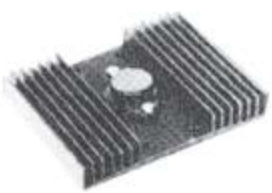









(a)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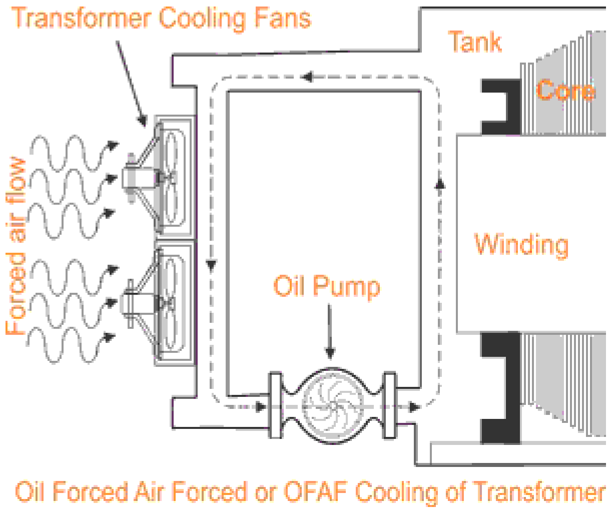
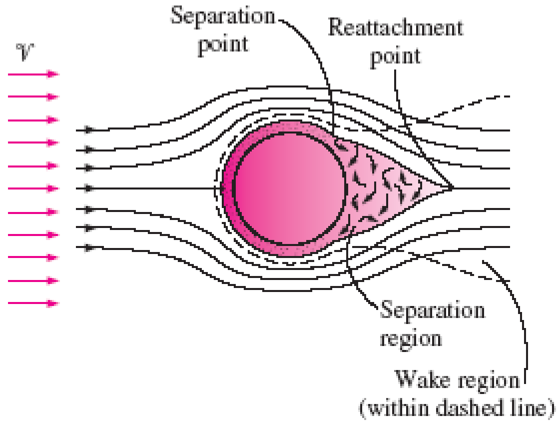
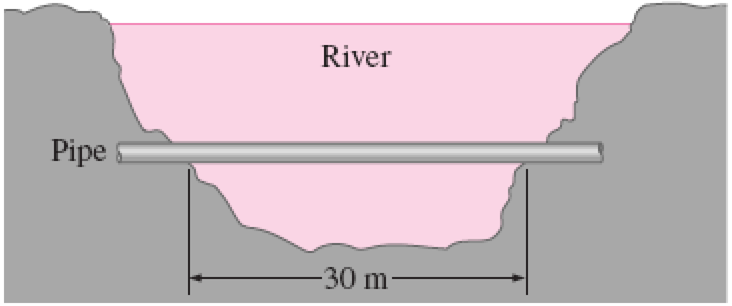
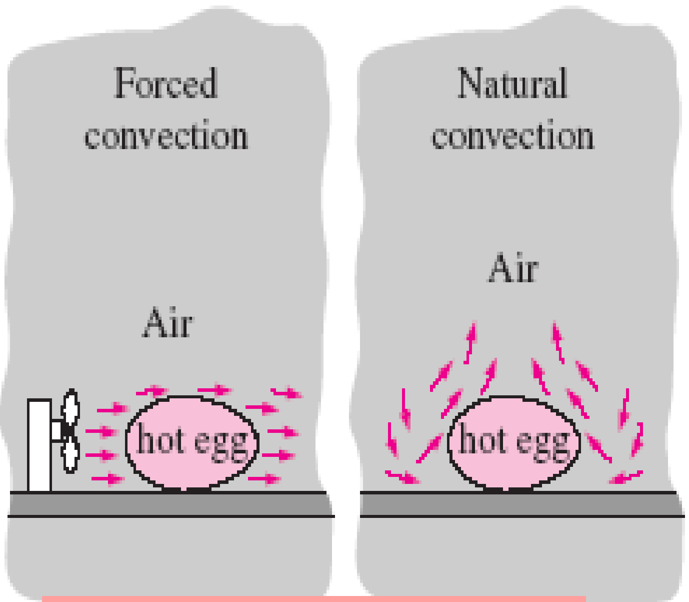


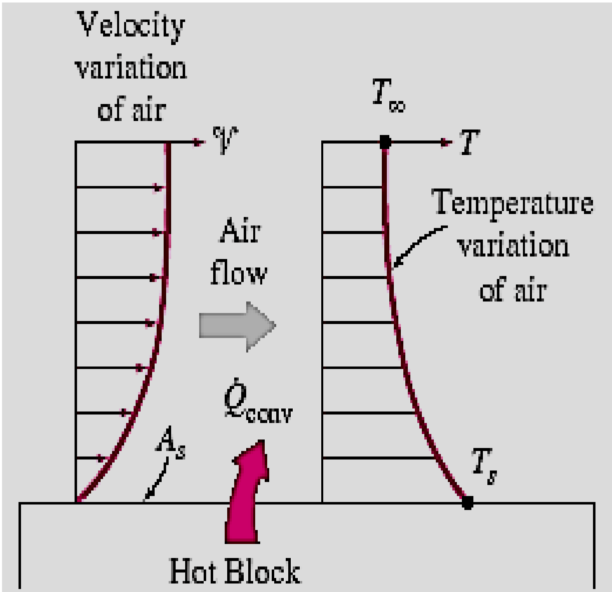


EXTERNAL FORCED CONVECTION



Heat Transfer Mechanisms - Convection





Type of convection	h, W/m^2 · °C*
Free convection of gases	2–25
Free convection of liquids	10–1000
Forced convection of gases	25–250
Forced convection of liquids	50–20,000
Boiling and condensation	2500–100,000

$$\dot{Q}_{conv} = h A_s (T_s - T_\infty) \qquad (W)$$

where h is the convection heat transfer coefficient in $W/m^2 \cdot °C$, A_s is the surface area through which convection heat transfer takes place, T_s is the surface temperature, and T_∞ is the temperature of the fluid sufficiently far from the surface. Note that at the surface, the fluid temperature equals the surface temperature of the solid.

Heat Transfer Mechanisms - Radiation

The maximum rate of radiation that can be emitted from a surface at an absolute temperature T_s (in K or R) is given by the **Stefan–Boltzmann law** as

$$\dot{Q}_{\text{emit, max}} = \sigma A_s T_s^4 \qquad \text{(W)}$$

where $\sigma = 5.67 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4$ or $0.1714 \times 10^{-8}\ \text{Btu/h} \cdot \text{ft}^2 \cdot \text{R}^4$ is the *Stefan–Boltzmann constant.*

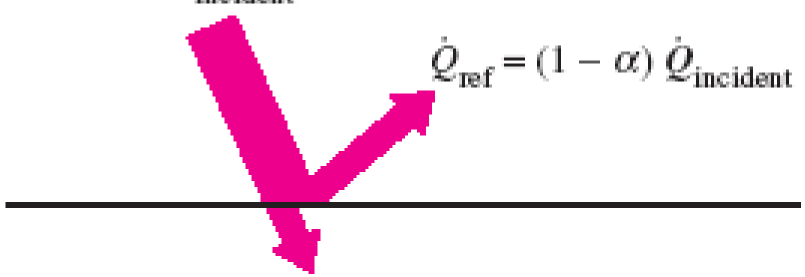
$$\dot{Q}_{\text{emit}} = \varepsilon \sigma A_s T_s^4 \qquad \text{(W)}$$

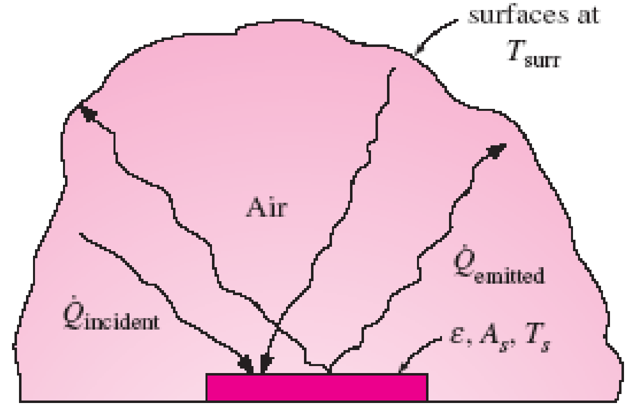
where ε is the **emissivity** of the surface.

$0 \le \varepsilon \le 1,$

Heat Transfer Mechanisms - Radiation

$$\dot{Q}_{rad} = \varepsilon\sigma A_s (T_s^4 - T_{surr}^4) \qquad \text{(W)}$$





Another important radiation property of a surface is its **absorptivity** α, which is the fraction of the radiation energy incident on a surface that is absorbed by the surface. Like emissivity, its value is in the range $0 \le \alpha \le 1$.

$$\dot{Q}_{absorbed} = \alpha\dot{Q}_{incident} \qquad \text{(W)}$$

Thermal Resistance Concept

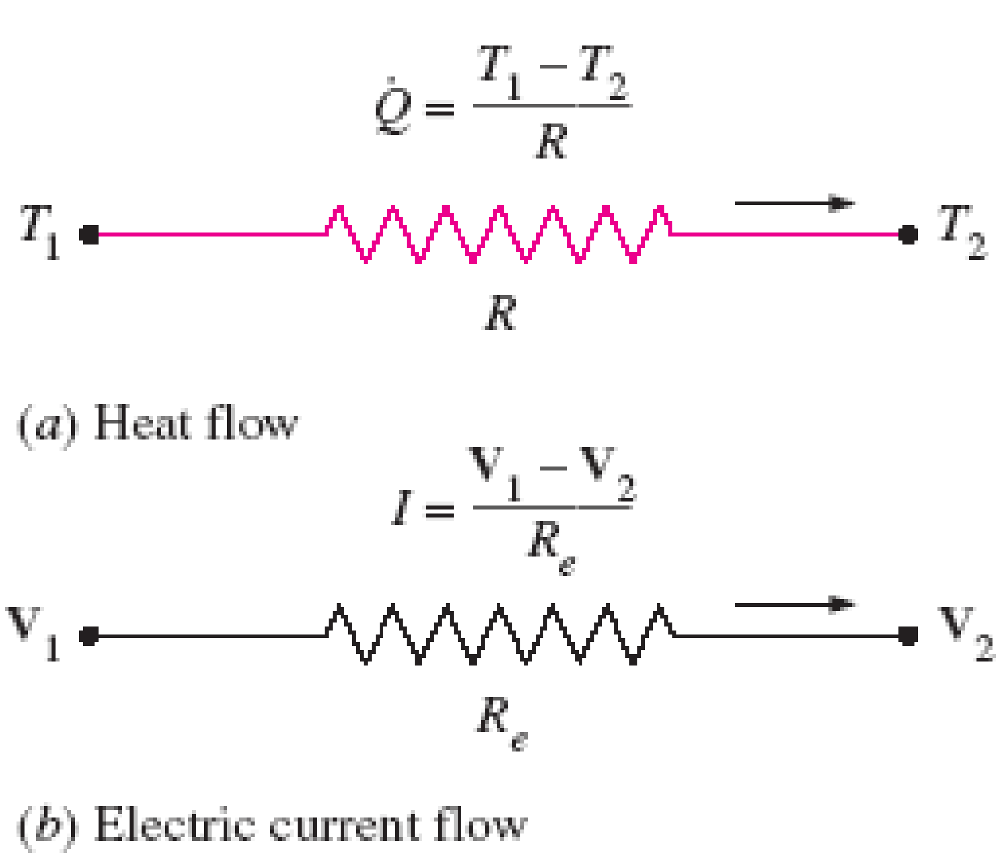
Conduction Thermal Resistance

$$\dot{Q}_{cond} = kA\frac{T_1 - T_2}{\Delta x} = -kA\frac{\Delta T}{\Delta x}$$

$$\dot{Q}_{\text{cond, wall}} = \frac{T_1 - T_2}{R_{\text{wall}}}$$

where

$$R_{\text{wall}} = \frac{L}{kA} \qquad (°\text{C/W})$$

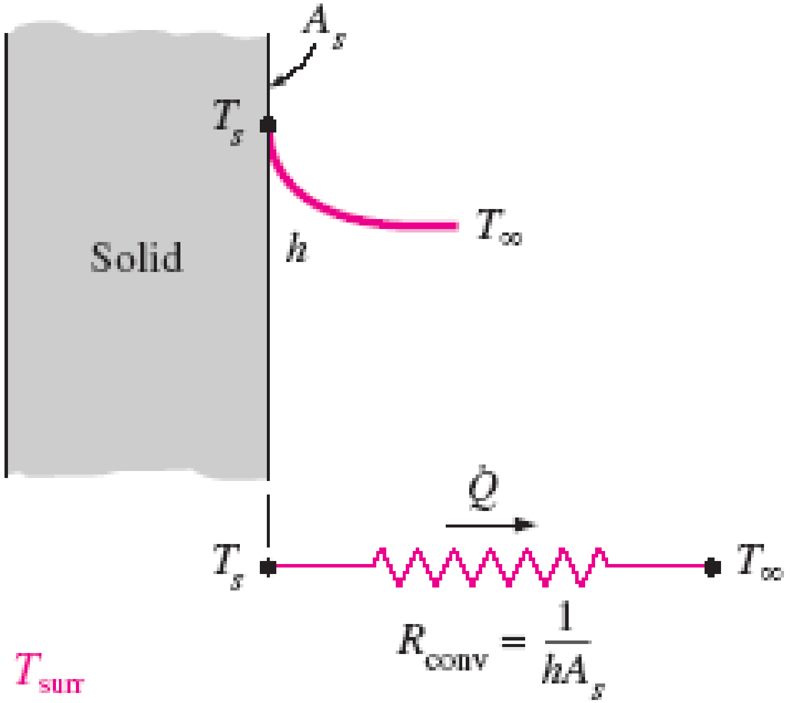


Thermal Resistance Concept

Convection Thermal Resistance

$$\dot{Q}_{\text{conv}} = \frac{T_s - T_\infty}{R_{\text{conv}}} \qquad \text{(W)}$$

where $R_{\text{conv}} = \dfrac{1}{hA_s}$ (°C/W)



Radiation Thermal Resistance

$$\dot{Q}_{\text{rad}} = \varepsilon\sigma A_s (T_s^4 - T_{\text{surr}}^4) = h_{\text{rad}} A_s (T_s - T_{\text{surr}}) = \frac{T_s - T_{\text{surr}}}{R_{\text{rad}}}$$

where $R_{\text{rad}} = \dfrac{1}{h_{\text{rad}} A_s}$ (K/W)

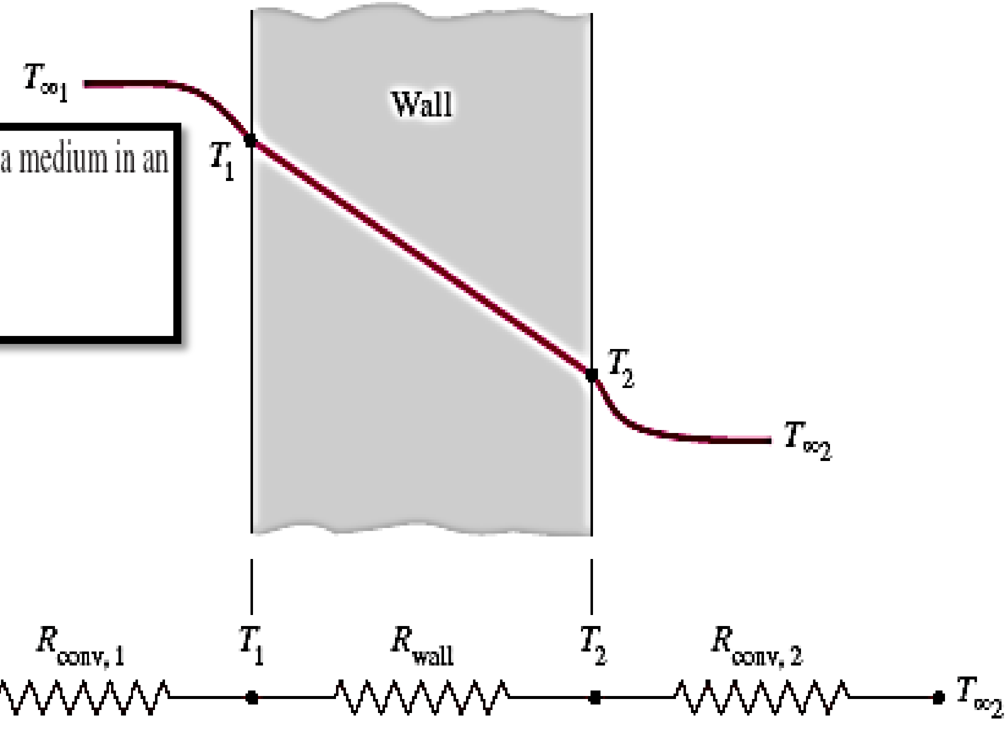
Thermal Resistance Concept

Thermal Resistance Network

It is sometimes convenient to express heat transfer through a medium in an analogous manner to Newton's law of cooling as

$$\dot{Q} = UA\,\Delta T \qquad \text{(W)}$$

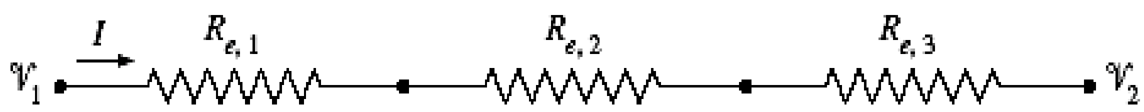
$$UA = \frac{1}{R_{total}}$$



$$\dot{Q} = \frac{T_{\infty 1} - T_{\infty 2}}{R_{conv,1} + R_{wall} + R_{conv,2}}$$

Thermal network

where U is the overall heat transfer coefficient.



$$I = \frac{\mathcal{V}_1 - \mathcal{V}_2}{R_{e,1} + R_{e,2} + R_{e,3}}$$

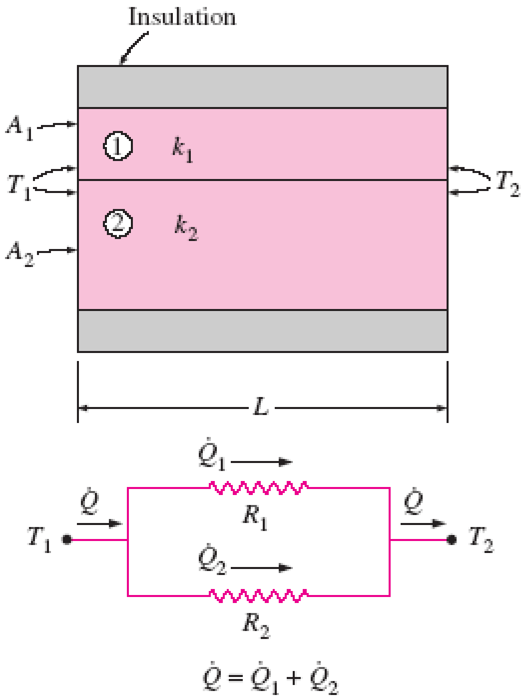
Electrical analogy

Thermal Resistance Concept

Thermal Resistance Network

$$\dot{Q} = \dot{Q}_1 + \dot{Q}_2 = \frac{T_1 - T_2}{R_1} + \frac{T_1 - T_2}{R_2} = (T_1 - T_2)\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

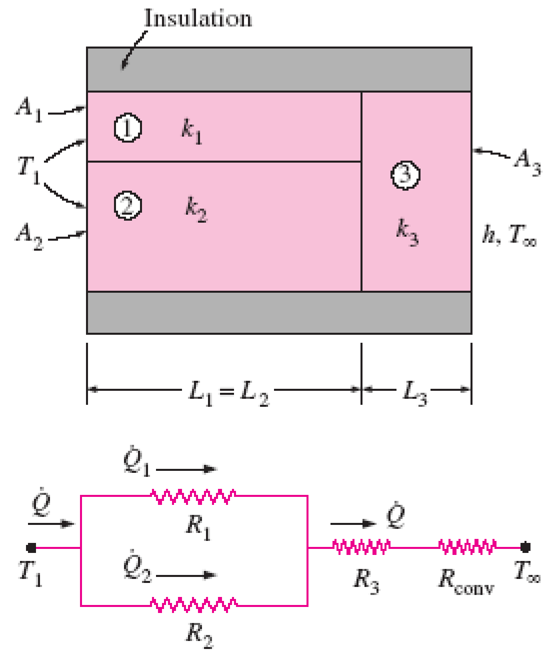
$$\dot{Q} = \frac{T_1 - T_2}{R_{\text{total}}} \qquad \frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} \longrightarrow R_{\text{total}} = \frac{R_1 R_2}{R_1 + R_2}$$



$$\dot{Q} = \frac{T_1 - T_\infty}{R_{\text{total}}}$$

$$R_{\text{total}} = R_{12} + R_3 + R_{\text{conv}} = \frac{R_1 R_2}{R_1 + R_2} + R_3 + R_{\text{conv}}$$

$$R_1 = \frac{L_1}{k_1 A_1}, \qquad R_2 = \frac{L_2}{k_2 A_2}, \qquad R_3 = \frac{L_3}{k_3 A_3}, \qquad R_{\text{conv}} = \frac{1}{hA_3}$$



Example 1: Heat transfer by Conduction

In a certain experiment, cylindrical samples of diameter 5 cm and length 10 cm are used. The two thermocouples in each sample are placed 3 cm apart. After initial transients, the electric heater is observed to draw 0.4 A at 110 V, and both differential thermometers read a temperature difference of 15°C. Determine the thermal conductivity of the sample.

$$\dot{W}_{elec} = VI = (110\,V)(0.4\,A) = 44\,W$$

The rate of heat flow through each sample is

$$\dot{Q} = 0.5\dot{W}_{elec} = 0.5 \times (44\,W) = 22\,W$$

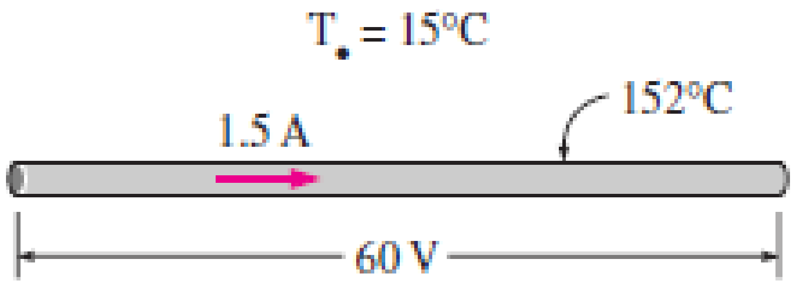
$$A = 0.25\pi \times (0.05\,m)^2 = 0.00196\ m^2$$

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

$$\Rightarrow k = \frac{\dot{Q}L}{A(T_1 - T_2)} = \frac{(22\,W)(0.03\,m)}{(0.00196\ m^2)(15\,°C)} = 22.4\,W/m.°C$$

Example 2: Heat transfer by Convection

A 2-m-long, 0.3-cm-diameter electrical wire extends across a room at 15°C, as shown in the following figure. Heat is generated in the wire as a result of resistance heating, and the surface temperature of the wire is measured to be 152°C in steady operation. Also, the voltage drop and electric current through the wire are measured to be 60 V and 1.5 A, respectively. Disregarding any heat transfer by radiation, determine the convection heat transfer coefficient for heat transfer between the outer surface of the wire and the air in the room.



Example 2: Heat transfer by Convection

$$\dot{Q} = \dot{E}_{generated} = VI = (60V)(1.5A) = 90W$$

The surface area of the wire is

$$A_s = \pi \times (0.003\,m) \times (2\,m) = 0.01885\ m^2$$

Newton's law of cooling for convection heat transfer is expressed as

$$\dot{Q}_{cov} = h A_s (T_s - T_\infty)$$

Disregarding any heat transfer by radiation and thus assuming all the heat loss from the wire to occur by convection, the convection heat transfer coefficient is determined to be

$$h = \frac{\dot{Q}_{conv}}{A_s (T_s - T_\infty)} = \frac{90W}{(0.01885\ m^2)(152 - 15)°C} = 34.9 W/m^2.°C \qquad \textbf{\textit{Ans.}}$$

Example 3: Heat transfer by Radiation

Consider a person standing in a room maintained at 22°C at all times. The inner surfaces of the walls, floors, and the ceiling of the house are observed to be at an average temperature of 10°C in winter and 25°C in summer. Determine the rate of radiation heat transfer between this person and the surrounding surfaces if the exposed surface area and the average outer surface temperature of the person are 1.4 m2 and 30°C, respectively. Take the emissivity of a person is 0.95

The net rates of radiation heat transfer from the body to the surrounding walls, ceiling, and floor in winter and summer are

$$\dot{Q}_{rad} = \varepsilon\sigma A_s\left(T_s^4 - T_{surr,\,winter}^4\right) = (0.95)(5.67\times10^{-8}\ W/m^2.K^4)(1.4\,m^2)$$
$$\times\left[(303)^4 - (283)^4\right] = 152\ W \qquad \textit{Ans.}$$

$$\dot{Q}_{rad} = \varepsilon\sigma A_s\left(T_s^4 - T_{surr,\,summer}^4\right) = (0.95)(5.67\times10^{-8}\ W/m^2.K^4)(1.4\,m^2)$$
$$\times\left[(303)^4 - (298)^4\right] = 40.9\ W \qquad \textit{Ans.}$$


QUIZ

Quiz

A transistor with a height of 0.4 cm and a diameter of 0.6 cm is mounted on a circuit board. The transistor is cooled by air flowing over it with an average heat transfer coefficient of 30 $W/m^2 \cdot °C$. If the air temperature is 55°C and the transistor case temperature is not to exceed 70°C, determine the amount of power this transistor can dissipate safely. Disregard any heat transfer from the transistor base.

Thank you