

Pertemuan ke-2

Operasi Perpindahan Kalor

Fundamentals of Heat Transfer

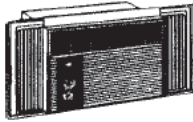
Outcome

- Menjelaskan **arah spontan** aliran panas dan **gaya pendorongnya** (ΔT), serta membedakan cakupan **termodinamika (equilibrium)** vs **perpindahan panas (non-equilibrium)**.
- Mengidentifikasi **tiga mode perpindahan panas** (konduksi, konveksi, radiasi) dan mengenali contoh nyata di sistem rekayasa.
- Menggunakan **Hukum Fourier** (bentuk beda hingga dan diferensial) beserta asumsi 1D steady state untuk menalar hubungan laju panas terhadap **k, A, ΔT , dan ketebalan**.
- Menjelaskan perbedaan **mekanisme konduksi** pada padat/cair/gas dan implikasinya pada **nilai konduktivitas termal**.
- Memodelkan konduksi steady 1D sebagai jaringan **thermal resistance**: dinding tunggal, dinding komposit, dan silinder (area berubah).
- Menalar bentuk **distribusi temperatur** pada konduksi dengan **heat generation** (dinding datar dan silinder) serta memahami mengapa temperatur maksimum sering terjadi **di bagian dalam** (hidden hotspot).

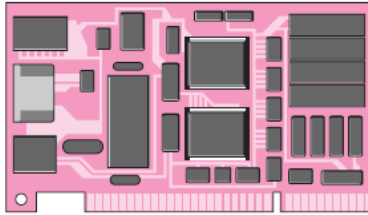
Fundamentals of Heat Transfer



The human body



Air-conditioning systems



Circuit boards

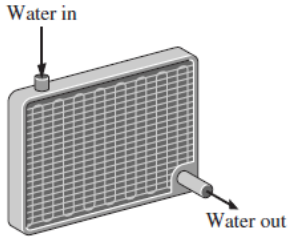


Hot coffee
70°C

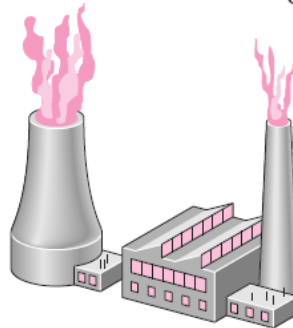
Heat

Cool environment
20°C

Heat Flows towards
Decreasing Temperature



Car radiators



Power plants

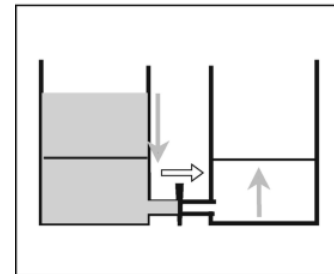


Refrigeration systems

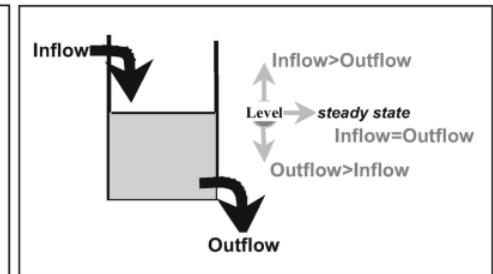
Application Areas of Heat Transfer

- ❖ Driving force for heat transfer: Temp. diff.
- ❖ Thermodynamics → Equilibrium
- Heat Transfer → Non-equilibrium

Equilibrium



Steady state



Thermodynamics vs Heat Transfer

Modes of Heat Transfer

❖ Conduction

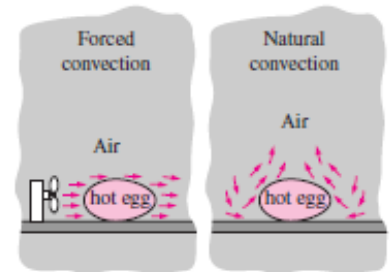
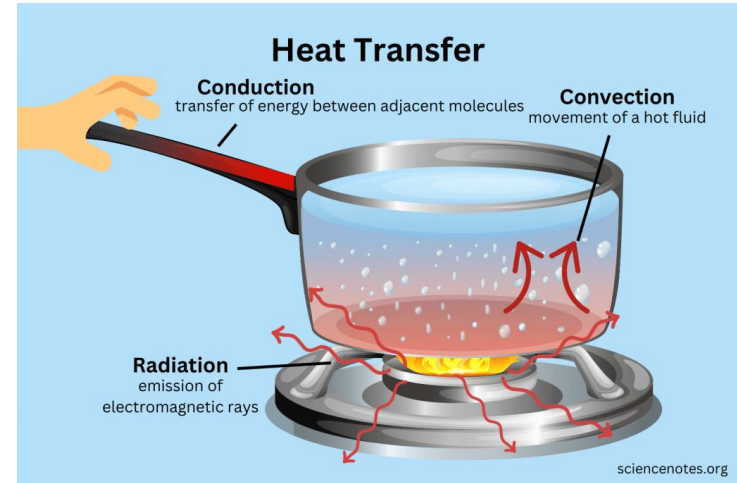
- Atomic/molecular process
- No macroscopic/bulk motion
- Sole mode of heat transfer in solid medium

❖ Convection

- Displacement of fluid elements
- Forced: Fluid is forced to flow by external mechanical energy
- Natural: Buoyancy forces induced by density differences due to temperature variation

❖ Radiation

- Thermal energy emitted in the form of electromagnetic waves
- Does not require intervening medium



Forced vs Natural Convection

Steady State Conduction in 1D

❖ Fourier's law

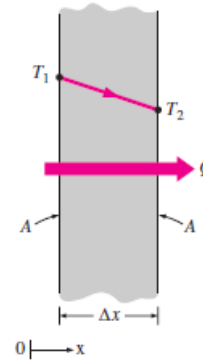
- Rate of heat transfer, $\dot{Q}_{\text{cond}} = kA \frac{T_1 - T_2}{\Delta x} = -kA \frac{\Delta T}{\Delta x}$
- Differential form ($\Delta x \rightarrow 0$),

$$\dot{Q}_{\text{cond}} = -kA \left(\frac{dT}{dx} \right)$$

Temp. Gradient

Thermal Conductivity (W/m °C)

Area (m²)



Plane Wall ($T_1 > T_2$)

$$\Delta T = T_2 - T_1$$

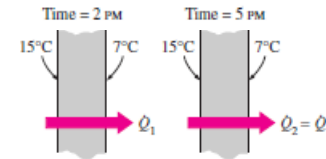
$$\Delta x = L$$

Rate of heat conduction $\propto \frac{(\text{Area})(\text{Temperature difference})}{\text{Thickness}}$

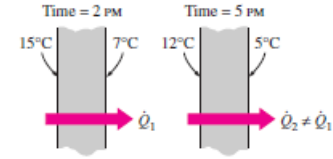
Experimental Observation

❖ Assumptions

- Steady state heat flow
 - No change in temp. and heat flux over time
- Heat flow in one dimensional only
 - No heat transfer in y and z directions



Steady State

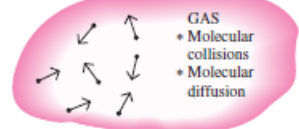
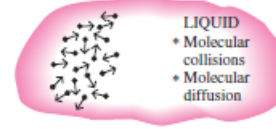
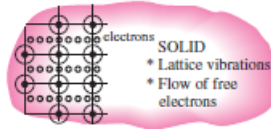


Unsteady State

Thermal Conductivity

❖ Mechanism of conduction

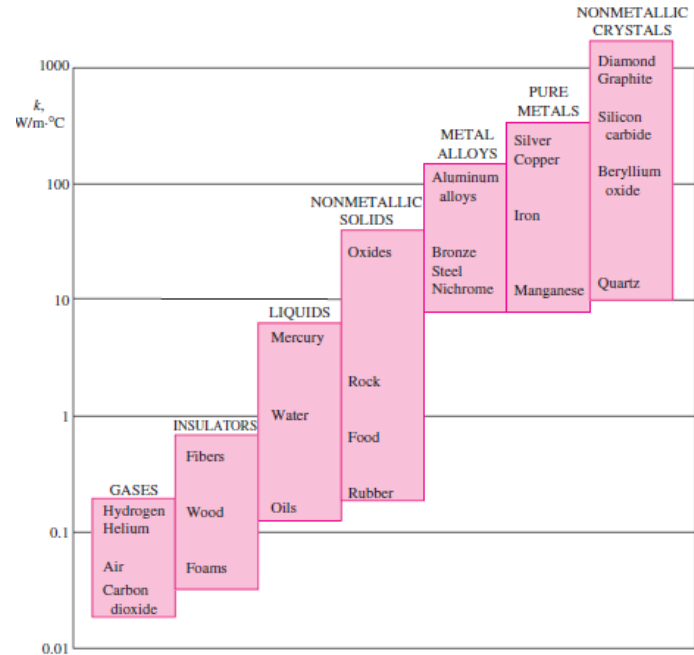
- Solids: lattice vibration (crystalline) and free flow of electrons (pure metal)
- Gases: Collision of molecules
- Liquids: Higher intermolecular forces than gases



Mechanism in Different Medium

❖ Thermal conductivity

- Fundamental property of a material
- Solids > Liquids > Gases
- Crystalline solid > Amorphous solid
- Insulators: Entrapped gases
- Effect of temperature and pressure



Range of Thermal Conductivity Values

Steady State Conduction in 1D: Single Wall

Energy balance,

$$\left(\begin{array}{c} \text{Rate of} \\ \text{heat transfer} \\ \text{into the wall} \end{array} \right) - \left(\begin{array}{c} \text{Rate of} \\ \text{heat transfer} \\ \text{out of the wall} \end{array} \right) = \left(\begin{array}{c} \text{Rate of change} \\ \text{of the energy} \\ \text{of the wall} \end{array} \right)$$

or, $\dot{Q}_{in} - \dot{Q}_{out} = \frac{dE_{wall}}{dt}$

❖ Assumptions

➤ Steady state heat flow

$$\frac{dE_{wall}}{dt} = 0$$

- No change in temp. and heat flux over time

➤ Heat flow in one dimensional only

- No heat transfer in y and z directions: $dT/dy \rightarrow 0$ & $dT/dz \rightarrow 0$

❖ Concept of Thermal Resistance

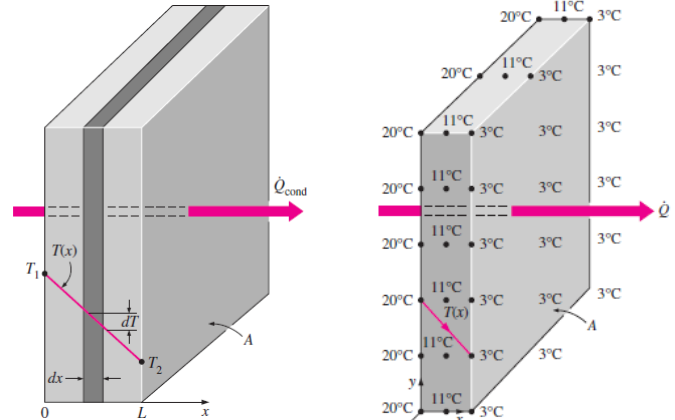
➤ For electric current flow, $\text{Current} = \frac{\text{Potential difference}}{\text{Electrical resistance}}$

➤ For heat flow, $\text{Rate of heat transfer} = \frac{\text{Temperature driving force}}{\text{Thermal resistance}}$

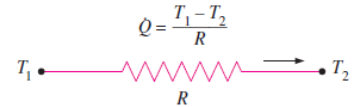
$$I = \frac{V_1 - V_2}{R_e}$$

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

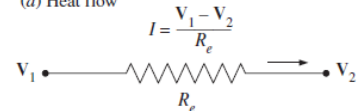
or, $R_{wall} = \frac{L}{kA}$



1D Heat Conduction in Single Wall



(a) Heat flow



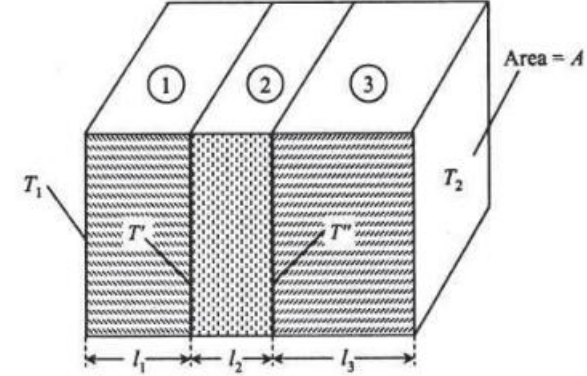
(b) Electric current flow

Analogy between Electrical and Thermal resistance

Steady State Conduction in 1D: Composite Wall

❖ Assumptions

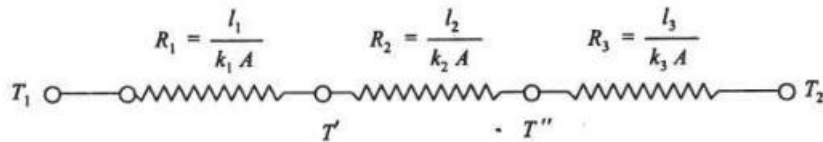
- Steady state heat flow
- Heat flow in one dimensional only
- Thermal conductivity is NOT a function of temperature
- Heat transfer area is constant



Heat Conduction in Composite Wall

$$\dot{Q} = \frac{T_1 - T_2}{\frac{l_1}{k_1 A} + \frac{l_2}{k_2 A} + \frac{l_3}{k_3 A}}$$

Rate of Heat Transfer



Electrical Analogue



Thermal resistances in series are additive

Steady State Conduction in 1D through Variable Area: Cylinder

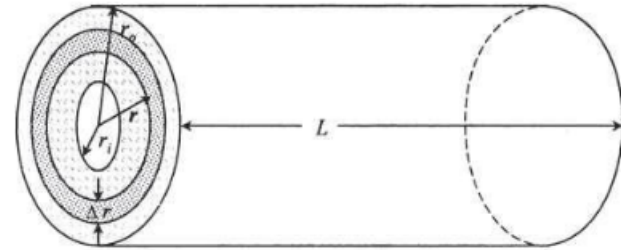
❖ Assumptions

- Steady state heat flow
- Heat flow in one dimensional only (long cylinder)
- Thermal conductivity is NOT a function of temperature

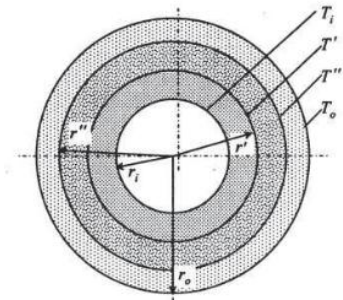
$$\dot{Q} = \frac{2\pi Lk(T_i - T_o)}{\ln(r_o/r_i)}$$

For composite cylinder,

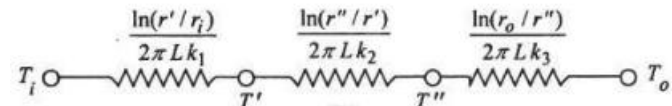
$$\dot{Q} = \frac{T_i - T_o}{\frac{\ln(r'/r_i)}{2\pi Lk_1} + \frac{\ln(r''/r')} {2\pi Lk_2} + \frac{\ln(r_o/r'')}{2\pi Lk_3}}$$



Heat Conduction through Hollow Cylinder



Heat Conduction through Composite Cylinder



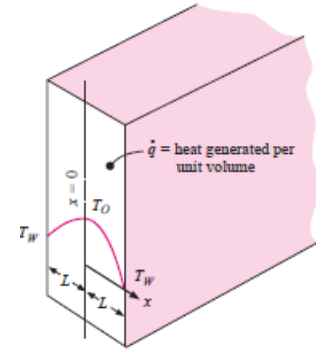
Electrical Analogue

Steady State Conduction with Heat Generation: Plane Wall

❖ Assumptions

- Steady state heat flow
- Heat flow in one dimensional only
- Thermal conductivity is NOT a function of temperature
- Heat transfer area is constant
- Heat generation per unit volume is constant

Temperature distribution,
$$\frac{T - T_0}{T_w - T_0} = \left(\frac{x}{L}\right)^2$$



Heat Generation in Single Wall

Steady State Conduction with Heat Generation: Plane Wall (Differential Approach)

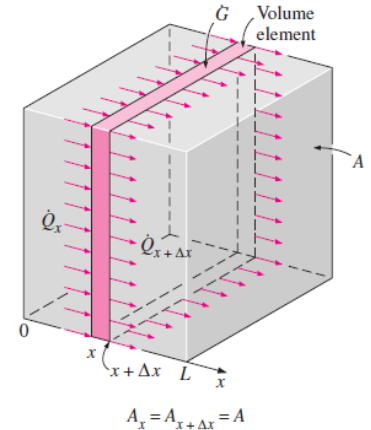
Energy balance,
$$\left(\begin{array}{c} \text{Rate of heat} \\ \text{conduction} \\ \text{at } x \end{array} \right) - \left(\begin{array}{c} \text{Rate of heat} \\ \text{conduction} \\ \text{at } x + \Delta x \end{array} \right) + \left(\begin{array}{c} \text{Rate of heat} \\ \text{generation} \\ \text{inside the} \\ \text{element} \end{array} \right) = \left(\begin{array}{c} \text{Rate of change} \\ \text{of the energy} \\ \text{content of the} \\ \text{element} \end{array} \right)$$

❖ Assumptions

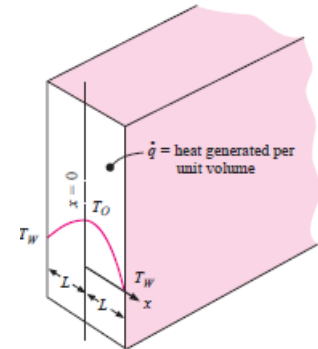
- Steady state heat flow
- Heat flow in one dimensional only
- Thermal conductivity is NOT a function of temperature
- Heat transfer area is constant
- Heat generation per unit volume is constant

Temperature distribution,
$$\frac{T - T_0}{T_w - T_0} = \left(\frac{x}{L} \right)^2$$

$$\frac{T - T_w}{T_0 - T_w} = 1 - \frac{x^2}{L^2}$$



1D Heat Conduction in Single Wall



Heat Generation in Single Wall

Steady State Conduction with Heat Generation: Cylinder

❖ Assumptions

- Steady state heat flow
- Heat flow in one dimensional only
- Thermal conductivity is NOT a function of temperature
- Heat generation per unit volume is constant

Heat generated within the cylinder of radius r
= Heat conducted through the cylinder at radius r

For solid cylinder,

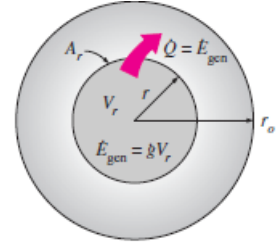
BC: At $r = 0$, $T = T_0$ and at $r = r_0$, $T = T_s$

Temperature rise, $\Delta T_{\max, \text{cylinder}} = T_o - T_s = \frac{\dot{g}r_o^2}{4k}$

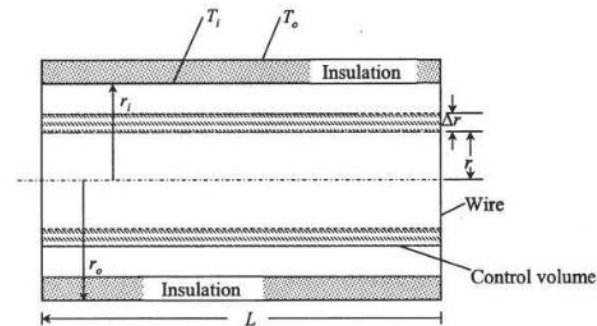
For insulated solid cylinder,

k_m & T_m = thermal conductivity and temperature of material of cylinder

k_c & T_c = thermal conductivity and temperature of insulation



Heat Generation in Solid Cylinder



Heat Generation in Insulated Solid Cylinder

THANK YOU