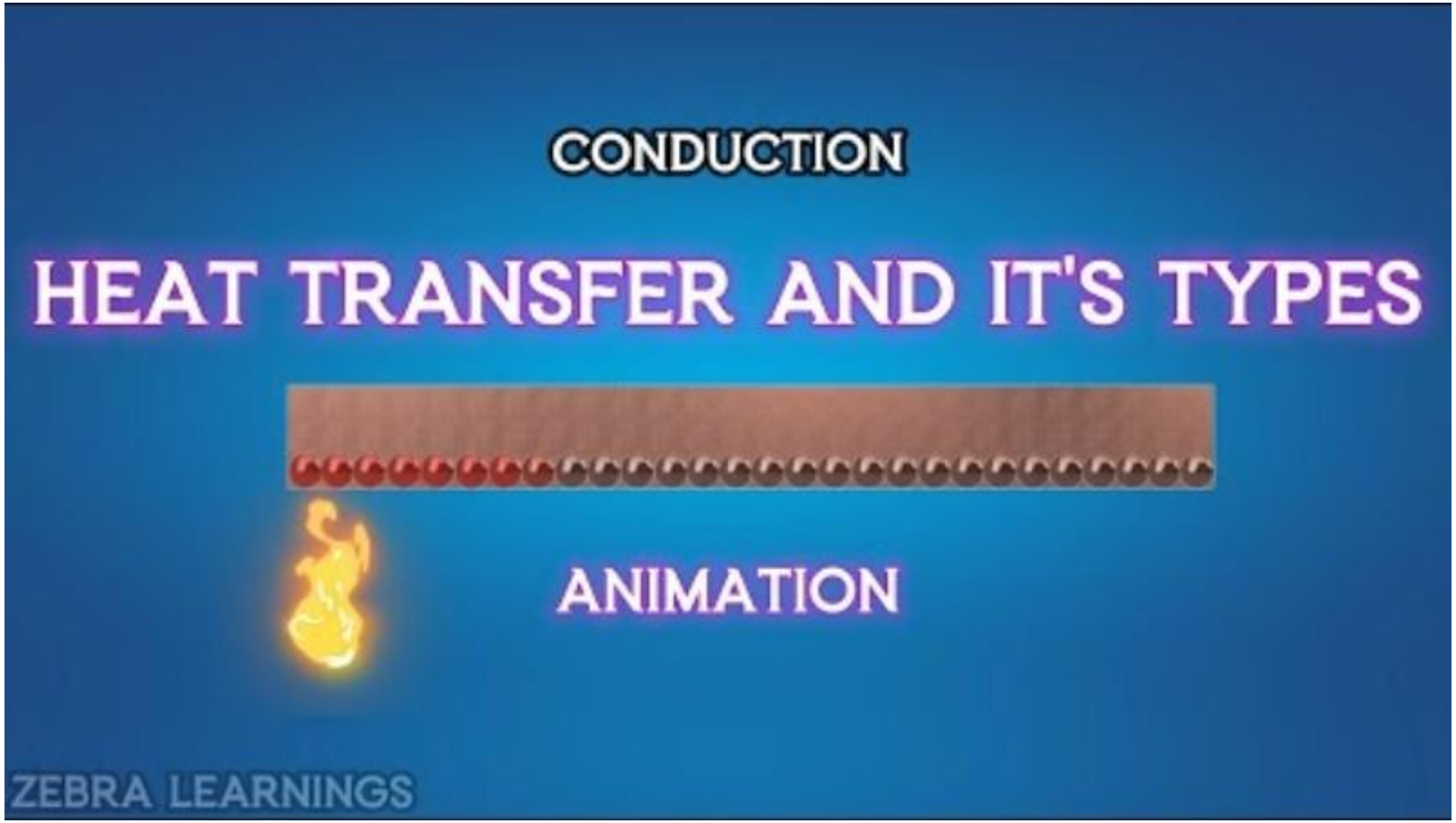
Pertemuan ke-4
Operasi Perpindahan Kalor

Fundamentals of Convection

Heat Transfer



Why does the spoon become hot when we stir hot water?

Heat flows from the hot water to the spoon through **convection** and **conduction**, then spreads along the spoon to your hand.

1 Hot water contains thermal energy
Water at higher temperature has more internal energy.

2 Convection in the water
Stirring creates bulk motion, bringing hot water in contact with the spoon surface.

3 Conduction at the interface
Heat transfers from the hot water molecules to the spoon surface by molecular interactions.

4 Conduction along the spoon
Heat conducts through the metal spoon from the immersed end toward the handle.

5 Heat reaches your hand
The handle becomes warm (or hot) as heat continues to conduct to your hand.

HEAT TRANSFER MODES

Convection
Heat is carried by the bulk motion of a fluid.

Conduction
Heat is transferred through a solid by molecular interactions.

Thermal Energy Flow
Heat always flows from higher temperature to lower temperature.

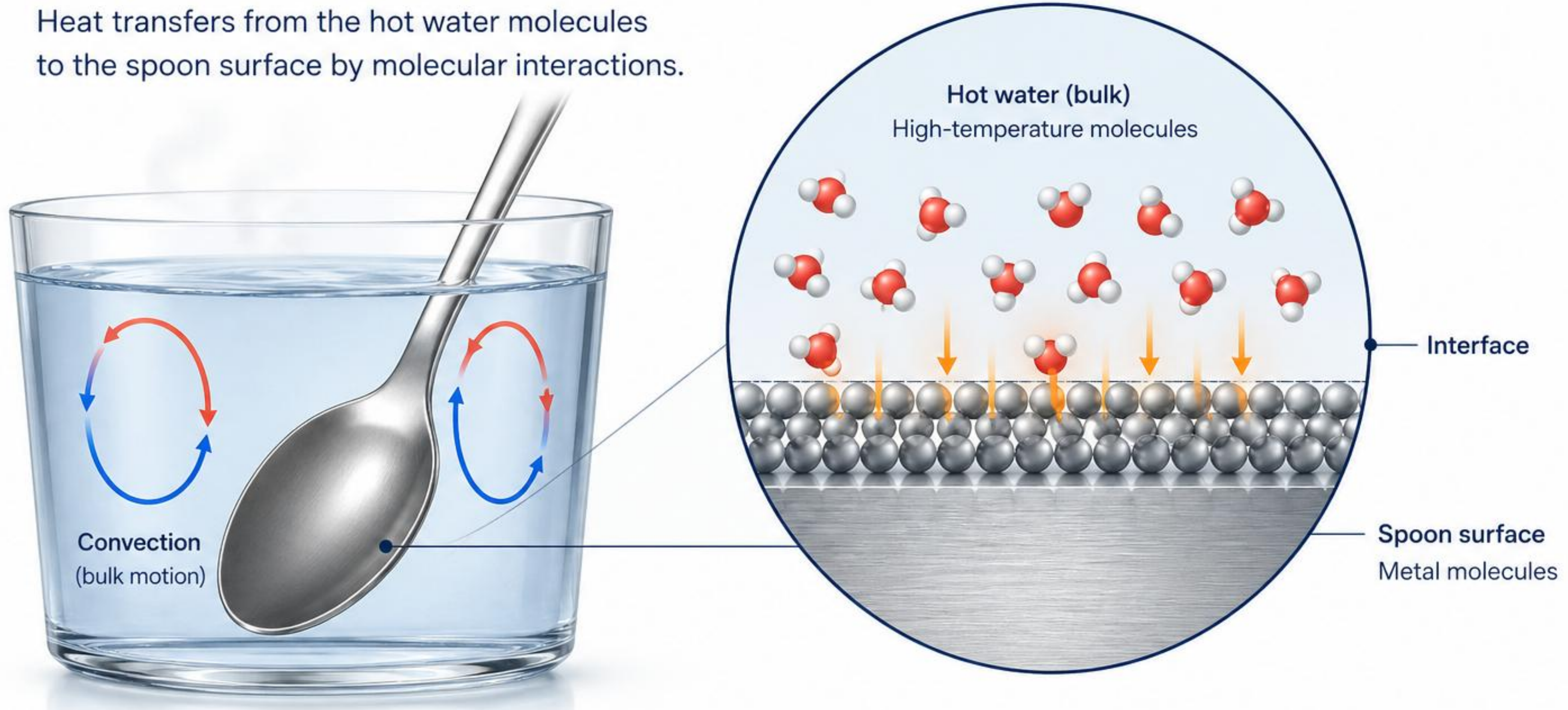
KEY TAKEAWAY
Stirring increases convection at the interface, enhancing heat transfer to the spoon. The metal then conducts heat efficiently to your hand.

THE PATH OF HEAT

1. **HOT WATER** — High temperature water
2. **CONVECTION (IN WATER)** — Stirring brings hot water into contact with spoon
3. **CONDUCTION (AT INTERFACE)** — Heat transfers from water to spoon surface
4. **CONDUCTION (THROUGH SPOON)** — Heat conducts along the metal spoon
5. **TO YOUR HAND** — Handle becomes warm or hot

3 Conduction at the interface

Heat transfers from the hot water molecules
to the spoon surface by molecular interactions.



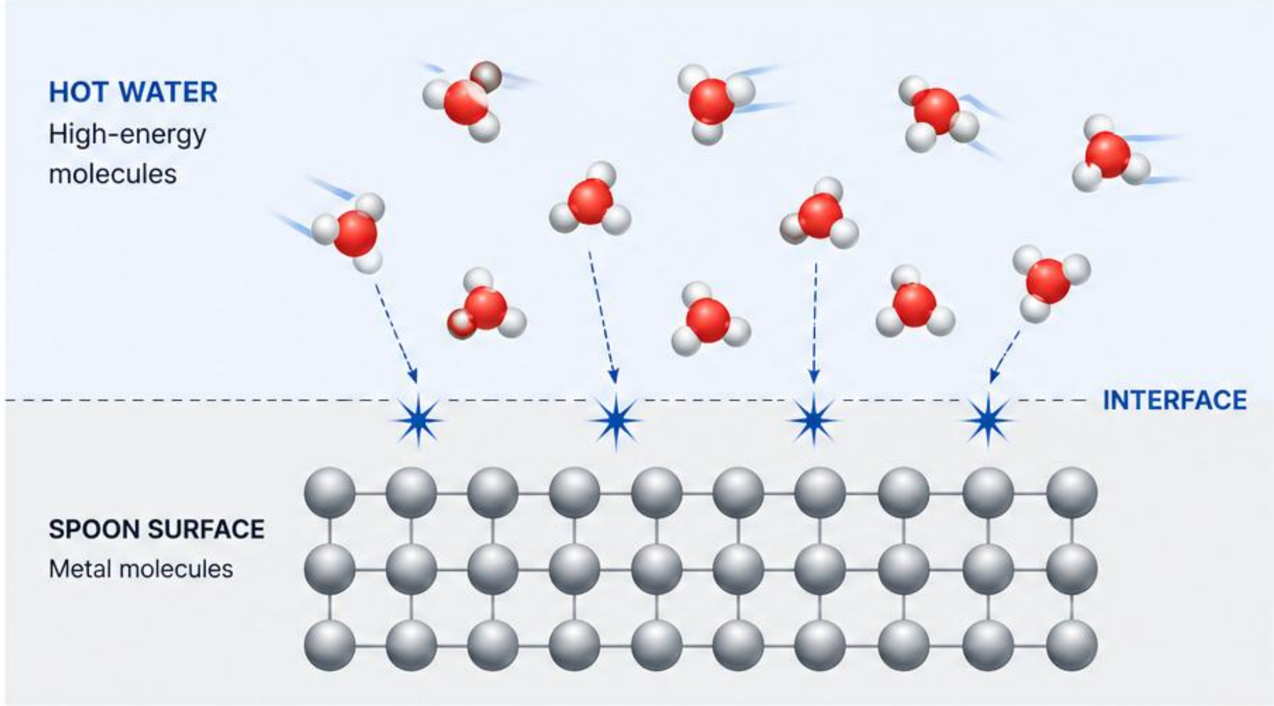
1. Hot water molecules have higher kinetic energy.
2. At the interface, molecules collide with and transfer energy to the metal surface.
3. The metal molecules absorb energy and vibrate more, increasing the spoon's temperature.

KEY TAKEAWAY Heat crosses the boundary not by bulk flow, but by molecular collisions and energy transfer at the interface.

AT THE INTERFACE

Molecular collisions transfer heat from hot water to the spoon

Heat crosses the boundary through **molecular collisions**, not by bulk flow.




Water molecule (high energy)

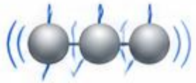

Metal molecule (lower energy)


Molecular collision (energy transfer)


1. High-energy water molecules move randomly in the bulk due to temperature.


2. Molecules near the surface collide with the spoon.


3. During collision, kinetic energy is transferred to metal molecules.

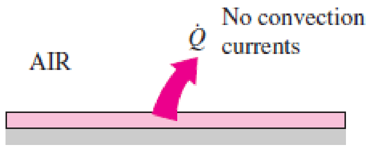

4. Metal molecules vibrate more and the heat spreads through the spoon by conduction.

KEY TAKEAWAY

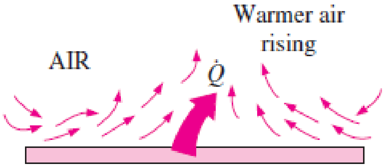
Heat transfer at the interface happens through molecular collisions and energy transfer, not through bulk movement of the fluid.

Fundamentals of Convection

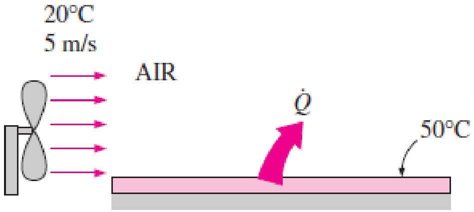
- Convection
  - Valid only for fluids (not solid)
  - Bulk/macroscopic motion of fluid elements
- Conduction in fluids
  - Caused by microscopic/molecular motion in fluids
  - Valid for stagnant fluids
  - Lower heat transfer rates than convection



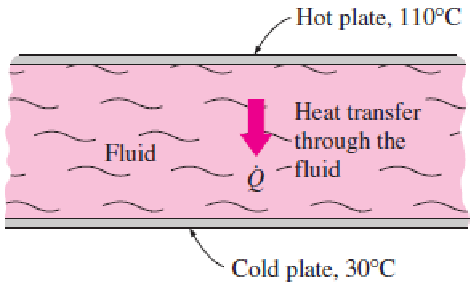
Conduction



Natural Convection



Forced Convection



Conduction in a Stagnant Fluid

Heat Transfer Coefficient

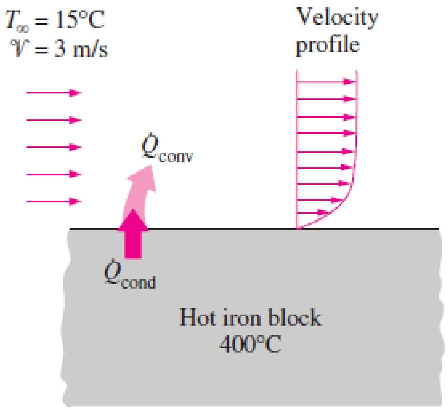
- Fluid flow over stationary surface
  - No slip condition
  - Conduction in fluid near surface
  - Decrease in thermal resistance with increasing fluid velocity
  - Measurement of heat transfer rate is complicated
- Alternate approach
  - Define heat transfer coefficient (h)
  - Phenomenological coefficient
  - Combines velocity, thermal conductivity, viscosity, density etc.
- Newton's law of cooling

$$\dot{Q}_{conv} \propto A_s$$

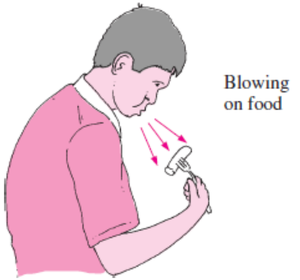
$$\dot{Q}_{conv} \propto (T_s - T_\infty)$$

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

$$\dot{q}_{conv} = h(T_s - T_\infty) \qquad (\text{W/m}^2)$$



Cooling of Hot Block by Forced Convection



Increased Cooling by Forced Convection

Film Theory

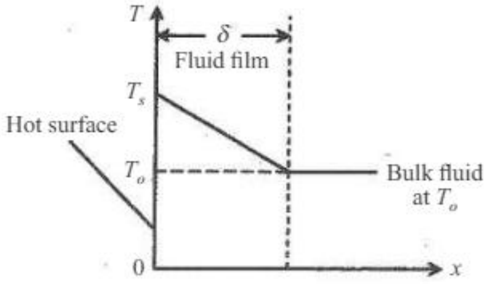
- Heat transfer to the adjacent film
  - Stagnant → Conduction
- Fourier's law

$$\dot{Q} = -kA\left(\frac{T_o - T_s}{\delta}\right) \quad = \frac{k}{\delta}A(T_s - T_o)$$

- Newton's law of cooling

$$\dot{Q} = hA(T_s - T_o)$$

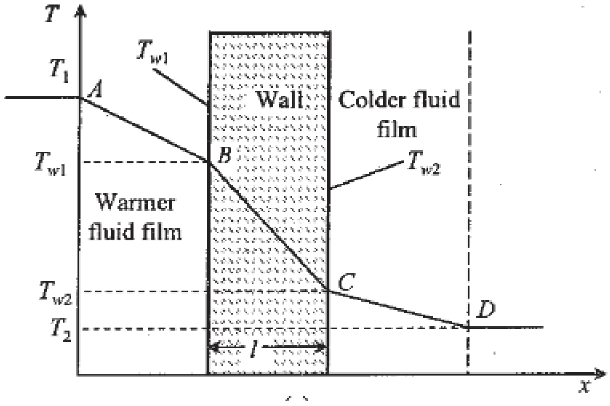
- Comparing the above, $h = \dfrac{k}{\delta}$
- The effect of fluid properties (velocity, viscosity etc.) are lumped in film thickness
- Stagnant film → Fictitious film
  - Film thickness can't be measured experimentally
  - Heat transfer coefficient values are determined from empirical correlations



Heat Transfer in a Stagnant Fluid

Heat Transfer through 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

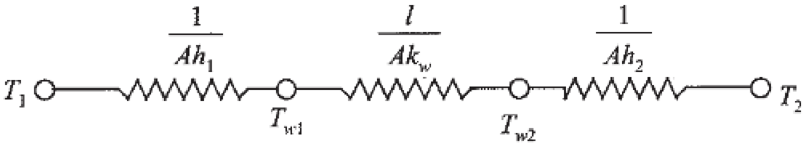


Convective Heat Transfer between Two Fluids

For steady state,

$$\begin{pmatrix}\text{Rate of}\\ \textit{heat convection}\\ \text{into the wall}\end{pmatrix} = \begin{pmatrix}\text{Rate of}\\ \textit{heat conduction}\\ \text{through the wall}\end{pmatrix} = \begin{pmatrix}\text{Rate of}\\ \textit{heat convection}\\ \text{from the wall}\end{pmatrix}$$

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



Electrical Analogue

- Controlling resistance
  - Metal wall vs gas phase resistance

Heat Transfer through Multilayered 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

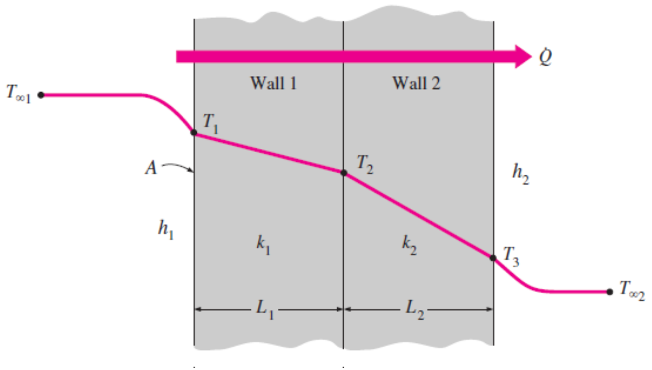
For steady state,

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

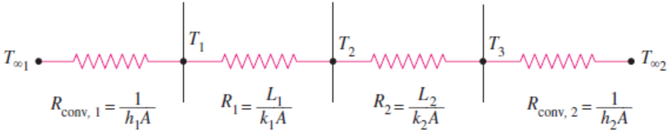
$$\dot{Q} = \frac{T_{\infty 1} - T_{\infty 2}}{R_{total}}$$

$$R_{total} = R_{conv,1} + R_{wall,1} + R_{wall,2} + R_{conv,2}$$

$$= \frac{1}{h_1 A} + \frac{L_1}{k_1 A} + \frac{L_2}{k_2 A} + \frac{1}{h_2 A}$$



Convective Heat Transfer between Two Fluids through Multilayered Plane Walls

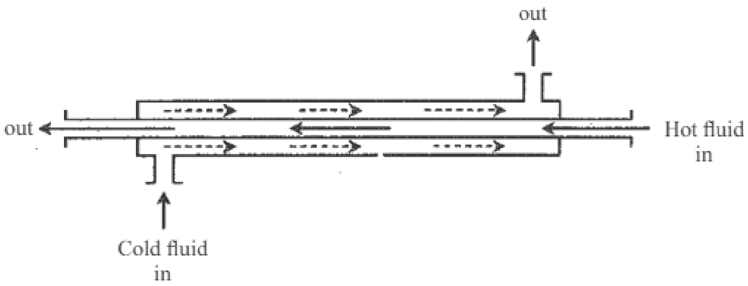


Electrical Analogue*

*Useful only for constant $\dot{Q}$ i.e., steady state with no heat generation

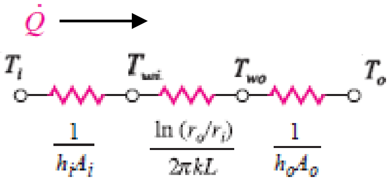
Heat Transfer through Cylindrical Wall

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



Schematic of Counter Current Double Pipe Heat Exchanger

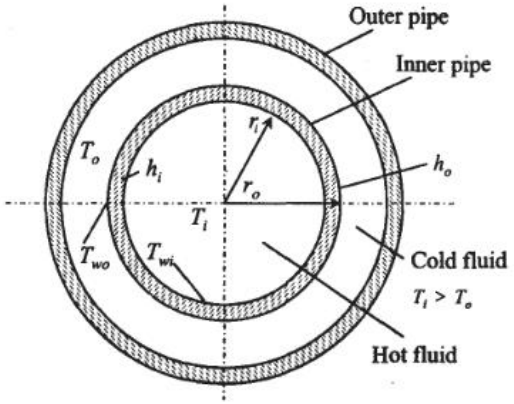
$$\dot{Q} = \frac{T_i - T_o}{\frac{1}{A_i h_i} + \frac{\ln(r_o/r_i)}{2\pi k_w L} + \frac{1}{A_o h_o}}$$



Electrical Analogue

$$U_i = \frac{1}{\frac{1}{h_i} + \frac{r_i \ln(r_o/r_i)}{k_w} + \frac{r_i}{r_o h_o}}$$

$$U_o = \frac{1}{\frac{r_o}{r_i h_i} + \frac{r_o \ln(r_o/r_i)}{kw} + \frac{1}{h_o}}$$



Cross-Sectional View

Heat Transfer from Extended Surfaces

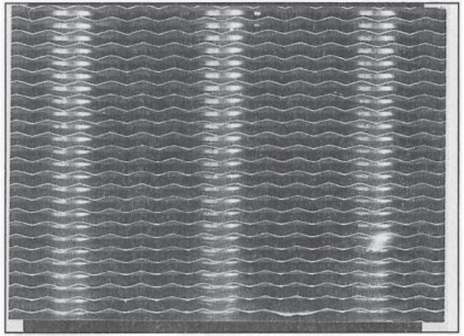
- Newton's law of cooling,

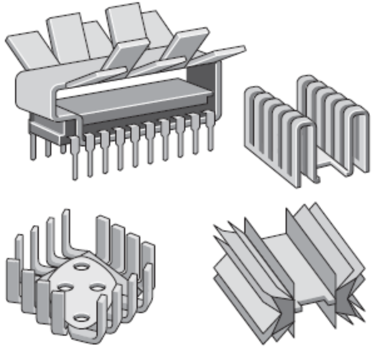
$$\dot{Q}_{conv} = hA_s(T_s - T_\infty)$$

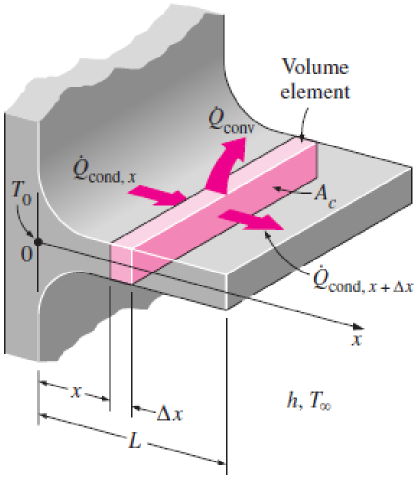
- Assumptions
  - Steady state heat flow
  - Heat flow in one dimensional only
  - Thermal conductivity is NOT a function of temperature
  - Heat transfer coefficient is constant
  - No heat generation

For steady state,

$$\begin{pmatrix}\text{Rate of } \textit{heat} \\ \textit{conduction} \text{ into} \\ \text{the element at } x\end{pmatrix} = \begin{pmatrix}\text{Rate of } \textit{heat} \\ \textit{conduction} \text{ from the} \\ \text{element at } x + \Delta x\end{pmatrix} + \begin{pmatrix}\text{Rate of } \textit{heat} \\ \textit{convection} \text{ from} \\ \text{the element}\end{pmatrix}$$


Thin Plate Fins in Car Radiator


Various Fin Designs



Heat Transfer from Finned Surface

Heat Transfer from Extended Surfaces: Various Scenarios

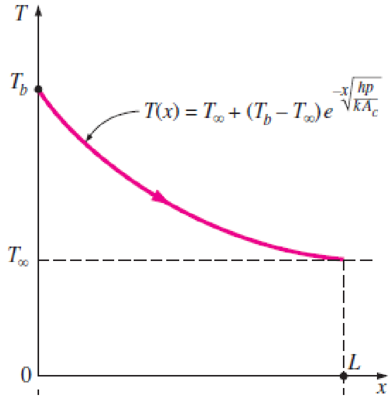
- Case 1: Infinitely long fin

$$\dot{Q}_{\text{long fin}} = \sqrt{hpkA_c}\,(T_b - T_\infty)$$

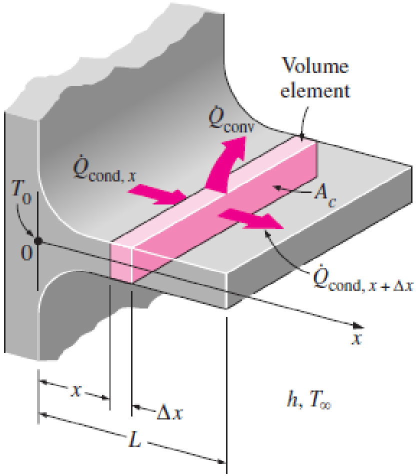
- Case 2: Negligible heat loss from fin tip
  - Insulated fin tip

$$\dot{Q}_{\text{insulated tip}} = \sqrt{hpkA_c}\,(T_b - T_\infty)\tanh aL$$

- Case 3: Finite length of fin and significant heat loss by convection
  - Complicated and lengthy expression



Temperature Distribution in Very Long Fin



Heat Transfer from Finned Surface

Fin Efficiency and Effectiveness

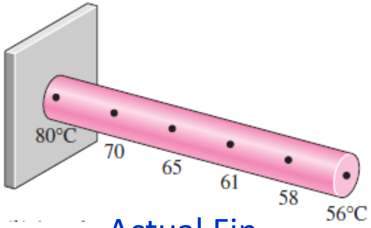
- Actual vs Ideal fin
  - Decreasing driving force towards fin tip
  - Fin efficiency,

$$\eta_{fin} = \frac{\dot{Q}_{fin}}{\dot{Q}_{fin,\,max}} = \frac{\text{Actual heat transfer rate from the fin}}{\text{Ideal heat transfer rate from the fin if the entire fin were at base temperature}}$$

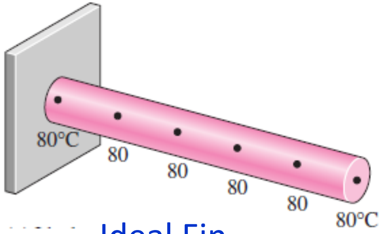
- Desired fin efficiency
  - Min: 60%; Preference: 90%
- Fin effectiveness,

$$\varepsilon_{fin} = \frac{\dot{Q}_{fin}}{\dot{Q}_{no\ fin}} = \frac{\dot{Q}_{fin}}{hA_b\,(T_b - T_\infty)} = \frac{\text{Heat transfer rate from the fin of } \textit{base area } A_b}{\text{Heat transfer rate from the surface of } \textit{area } A_b}$$

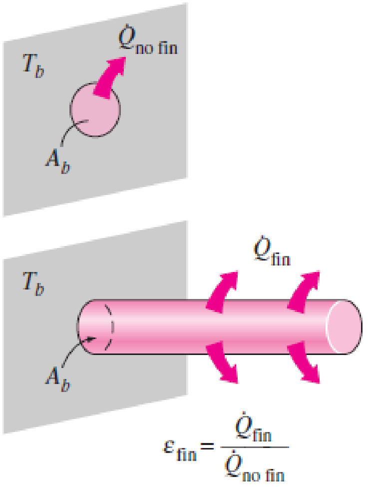
- Proper length of fin
  - Effect of excess length on weight/size/cost/h



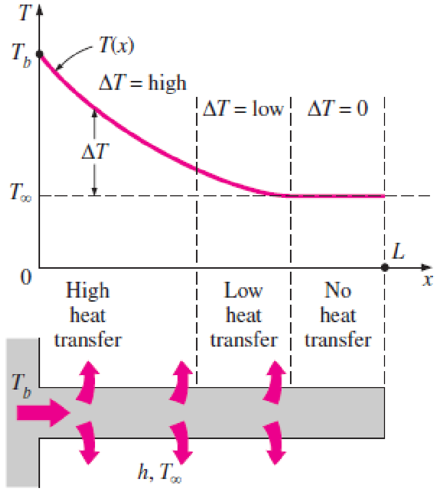
Actual Fin



Ideal Fin



Fin Effectiveness



Determination of Desirable Fin Length

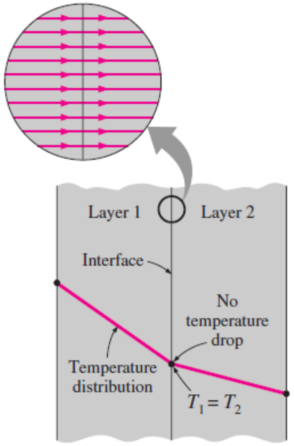
Thermal Contact Resistance

- Previous assumption for multilayered solids
  - Perfectly smooth surfaces
  - Perfect contact
- Real surfaces
  - Microscopically rough
- Heat transfer contribution at the interface through
  - Solid contact points
  - Gaps in noncontact areas

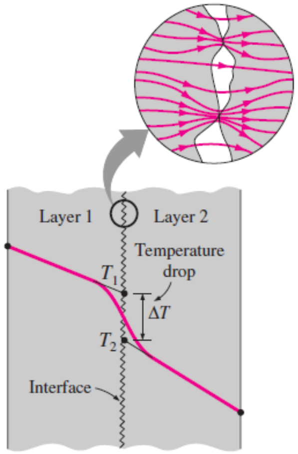
$$\dot{Q} = \dot{Q}_{\text{contact}} + \dot{Q}_{\text{gap}}$$

contact coefficient

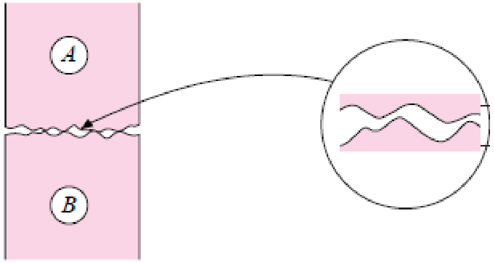
- Analogous expression, $\dot{Q} = h_c A \, \Delta T_{\text{interface}}$
- Thermal contact resistance, $1/h_c A$
  - Effect of roughness and pressure
- Possible solution: thermal grease and conducting gas



Thermal Contact (Ideal)



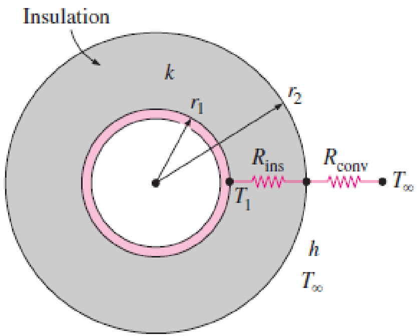
Thermal Contact (Real)



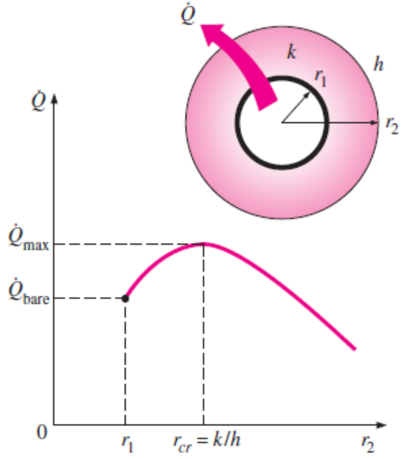
Thermal Contact Resistance

Critical Radius of Insulation

- Insulation in wall
  - Thicker insulation → lower $\dot{Q}$
- Insulation in cylindrical pipe/spherical shell
  - Increase in conduction resistance
  - Decrease in convection resistance
- Effect of critical radius of insulation in
  - Steam pipe
  - Electrical wire



Insulated Cylindrical Pipe



Effect of Radius of Insulation on Heat Transfer Rate

THANK YOU