

CONDUCTIVE HEAT TRANSFER

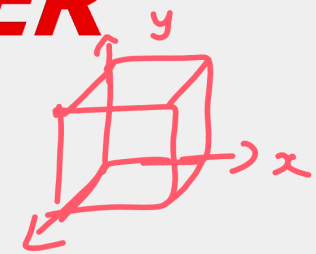
$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}}{k} = \frac{1}{\alpha} \cdot \frac{\partial T}{\partial t}$$

Cond'n eqn in Cartesian Co-ordinates.

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \cdot \frac{\partial T}{\partial t}$$

$\alpha \rightarrow$ Thermal diffusivity.

unsteady.



CONDUCTIVE HEAT TRANSFER

✓ $\Rightarrow$ lumped parameter analysis.
 (Bi < 0.1)

$$\frac{T - T_{\infty}}{T_b - T_{\infty}} = e^{\left(\frac{-hA}{\rho c v} \right) \tau}$$

$T_b \rightarrow$ base temp
 $T \rightarrow$ Temp at specific time.

$\tau \rightarrow$ time.

$$\frac{A}{V} \rightarrow \left(\frac{V}{A} = L_c \right)$$

$L_c \rightarrow$ Characteristic length.

CONDUCTIVE HEAT TRANSFER

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$\tau \rightarrow$ time.

$h \rightarrow$

lumped
 parameter
 analysis.

$(Bi < 0.1)$

$T_b \rightarrow$ base temp

$T \rightarrow$ Temp at specific time.

$Bi < 0.1$

$Q_{conv} \gg Q_{cond.}$

$\frac{R_{conv}}{R_{cond}} < 0.1$

$\Rightarrow Q_{conv} \uparrow Q_{cond.}$

$\frac{A}{V} \rightarrow \frac{V}{A} = L_c$

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CONDUCTIVE HEAT TRANSFER

Lumped parameter analysis.
 $(Bi < 0.1)$

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$\tau \rightarrow$ time.

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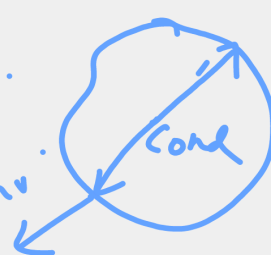
$L_c \rightarrow$ Characteristic length.

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$\frac{R_{conv}}{R_{cond}} < 0.1 \Rightarrow Q_{conv} \uparrow Q_{cond}$

$Q_{conv} \gg Q_{cond}$



CONDUCTIVE HEAT TRANSFER

✓
lumped
parameter
analysis.

$(Bi < 0.1)$

$\uparrow$
 $Q_{conv} \gg Q_{cond} \downarrow$

$$\frac{T - T_{\infty}}{T_b - T_{\infty}} = e^{\left(\frac{-hA}{\rho c v} \right) T}$$

$h \rightarrow$

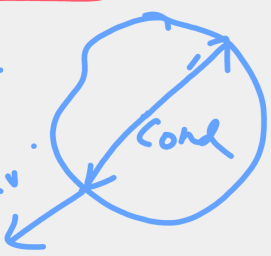
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$Bi = \frac{hL}{k}$

$T \rightarrow$ time.

$\frac{A}{V} \rightarrow \frac{V}{A} = L_c$

$L_c \rightarrow$ Characteristic length.

Lumped System Analysis

The lumped system analysis is more likely to be applicable for the body cooled naturally since the Biot number is proportional to the convection heat transfer coefficient, which is proportional to the air velocity. Therefore, the Biot number is more likely to be less than 0.1 for the case of natural convection.

$$Bi = \frac{hL}{k}$$

$$Bi \propto h$$
$$Bi \propto \frac{1}{k}$$

Lumped System Analysis

$$Bi = \frac{R_{cond}}{R_{conv}} = 0.1 \quad R_{cond} = 0.1 R_{conv}$$

In heat transfer analysis, some bodies are observed to behave like a "lump" whose entire body temperature remains essentially uniform at all times during a heat transfer process. The temperature of such bodies can be taken to be a function of time only. Heat transfer analysis which utilizes this idealization is known as the lumped system analysis. It is applicable when the Biot number (the ratio of conduction resistance within the body to convection resistance at the surface of the body) is less than or equal to 0.1.

Lumped System Analysis

$$Bi = \frac{hL}{k} = \frac{Q_{conv}}{Q_{cond}} \quad Bi = \frac{R_{cond}}{R_{conv}} = 0.1 \quad \underline{R_{cond} = 0.1 R_{conv}}$$

In heat transfer analysis, some bodies are observed to behave like a "lump" whose entire body temperature remains essentially uniform at all times during a heat transfer process. The temperature of such bodies can be taken to be a function of time only. Heat transfer analysis which utilizes this idealization is known as the lumped system analysis. It is applicable when the Biot number (the ratio of conduction resistance within the body to convection resistance at the surface of the body) is less than or equal to 0.1.

CONDUCTIVE HEAT TRANSFER

3. Numerical: A plane wall 10 cm thick has a thermal conductivity of 15 W/m·K. If the temperature difference across the wall is 100°C, the heat flux (q) is:

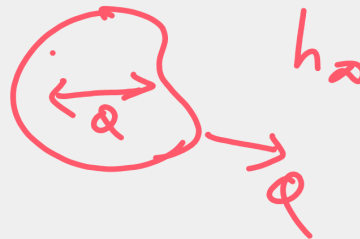
- A) 150 W/m²
- B) 1500 W/m²
- C) 15000 W/m²
- D) 1.5 W/m²

$$\frac{T - T_{\infty}}{T_b - T_{\infty}} = e^{\left(\frac{-hA}{\rho c v} \right) L}$$

$$\rho = \frac{m}{V}$$

4. The ratio of internal conductive resistance to external convective resistance is known as:

- A) Nusselt Number
- ✓ B) Biot Number
- C) Prandtl Number
- D) Grashof Number



$$\Rightarrow m c \frac{dT}{dt} = -hA \frac{dT}{dt}$$

$$\rho V c \cdot \frac{dT}{dt} = -hA \cdot \frac{dT}{dt}$$

CONDUCTIVE HEAT TRANSFER

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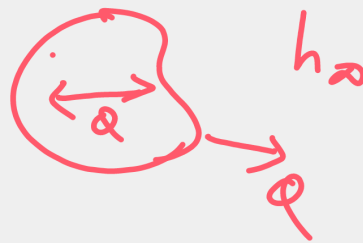
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$\rho = \frac{m}{V}$
Transient Conduction
eqn for lumped analysis

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- ✓ B) Biot Number
- C) Prandtl Number
- D) Grashof Number



$$\Rightarrow m \frac{dT}{dt} = -hA \frac{dT}{dt}$$

$$\rho V \cdot C \cdot \frac{dT}{dt} = -hA \cdot \frac{dT}{dt}$$

CONDUCTIVE HEAT TRANSFER

← Transient

5. For unsteady-state heat conduction, the Lumped Heat Capacity analysis is valid if the Biot number (Bi) is:

- ✓ A) $Bi < 0.1$
- B) $Bi > 1.0$
- C) $Bi = 0$
- D) $Bi > 10$

$$\underline{\underline{Bi < 0.1}}$$

6. Numerical: A copper sphere ($k = 380 \text{ W/m}\cdot\text{K}$) of diameter 10 mm is immersed in a fluid where $h = 10 \text{ W/m}^2\cdot\text{K}$. The Biot number for this system is approximately:

- ✓ A) 4.38×10^{-5}
- B) 8.76×10^{-4}
- C) 1.2×10^{-2}
- D) 2.1×10^{-5}

$$\frac{Bi < 0.1 \checkmark}{> 0.1}$$

$$Bi = \frac{hL_{\text{conv}}}{k} = \frac{10 \times 10}{380 \times 1000} \approx 4.4 \times 10^{-5}$$

CONDUCTIVE HEAT TRANSFER

$$\frac{T - T_{\infty}}{T_b - T_{\infty}} = e^{-\frac{hA}{\rho C_v} \tau}$$

3. GATE Mechanical PYQ Pattern: The Thermocouple Problem

Problem (Pattern: GATE 2010/2016): A thermocouple junction, approximated as a sphere, is used to measure the temperature of a gas stream ($T_{\infty} = 300^{\circ}\text{C}$). The junction is initially at 25°C . The properties are: $\rho = 8000 \text{ kg/m}^3$, $C_p = 400 \text{ J/kg}\cdot\text{K}$, $k = 20 \text{ W/m}\cdot\text{K}$. The convection coefficient is $h = 400 \text{ W/m}^2\cdot\text{K}$. If the junction must read 290°C within 1 second, what is the required diameter of the junction?

$$L_c = \frac{V}{A}$$

CONDUCTIVE HEAT TRANSFER

Solution:

Step 1: Use the Temperature Ratio $(T - T_{\infty}) / (T_i - T_{\infty}) =$
 $(290 - 300) / (25 - 300) = (-10) / (-275) = 0.03636$

Step 2: Solve for Time Constant $0.03636 = e^{(-t/\tau^*)}$

$$\ln(0.03636) = -1/\tau^* - 3.314 = -1/\tau^* \Rightarrow \tau^* = 0.3017 \text{ s}$$

*Step 3: Relate τ to Diameter** $\tau^* = \rho V C_p / (h A_s) = \rho (D/6) C_p / h$

$$0.3017 = [8000 \times (D/6) \times 400] / 400$$

$$0.3017 = 8000 \times (D/6)$$

$$D = (0.3017 \times 6) / 8000 = 0.000226 \text{ m} = 0.226 \text{ mm}$$

$$e^{-\frac{hA}{\rho C V}}$$
$$D = 2R$$
$$\left(\frac{V}{A}\right) = R$$

CONDUCTIVE HEAT TRANSFER

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Step 1: Use the Temperature Ratio $(T - T_{\infty}) / (T_i - T_{\infty}) =$
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✓
Temp Ratio
Time Const.
Bi
Lc

CONDUCTIVE HEAT TRANSFER

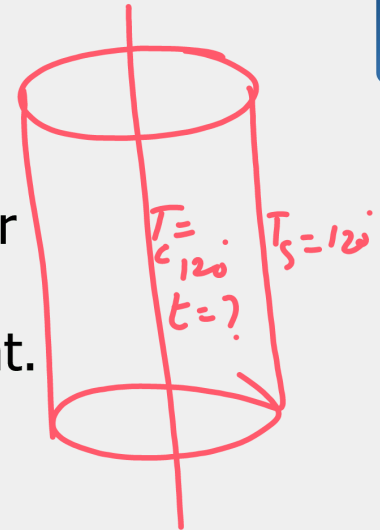
$$Bi = \frac{hL}{k}$$

A long cylindrical bar ($k = 17.4 \text{ W/m}^\circ\text{C}$, $\alpha = 0.019 \text{ m}^2/\text{h}$) of radius **80 mm** comes out of an oven at a uniform temperature of **830°C**. It is suddenly cooled by quenching in a large bath maintained at **40°C**. $\leftarrow T_\infty$.

The convective heat transfer coefficient between the bar surface and the coolant is **180 W/m²°C**. $\rightarrow h$.

Determine:

1. The time required for the **center** of the bar to reach **120°C**.
2. The **surface temperature** of the bar at the instant when the center temperature is **120°C**.
3. The **temperature gradient** at the outer surface at the same instant.



CONDUCTIVE HEAT TRANSFER

Given data

- Radius: $r_0 = 80 \text{ mm} = 0.08 \text{ m}$
- Initial temperature: $T_i = 830^\circ\text{C}$
- Ambient temperature: $T_\infty = 40^\circ\text{C}$
- Target center temperature: $T_c = 120^\circ\text{C}$
- $k = 17.4 \text{ W/m}^\circ\text{C}$
- $h = 180 \text{ W/m}^2^\circ\text{C}$
- Thermal diffusivity:
 $\alpha = 0.019 \text{ m}^2/\text{s} = 5.28 \times 10^{-6} \text{ m}^2/\text{s}$

Step 1: Biot Number

$$Bi = \frac{hr_0}{k}$$

$$\rightarrow \frac{hL}{k} = \frac{r_0}{L}$$

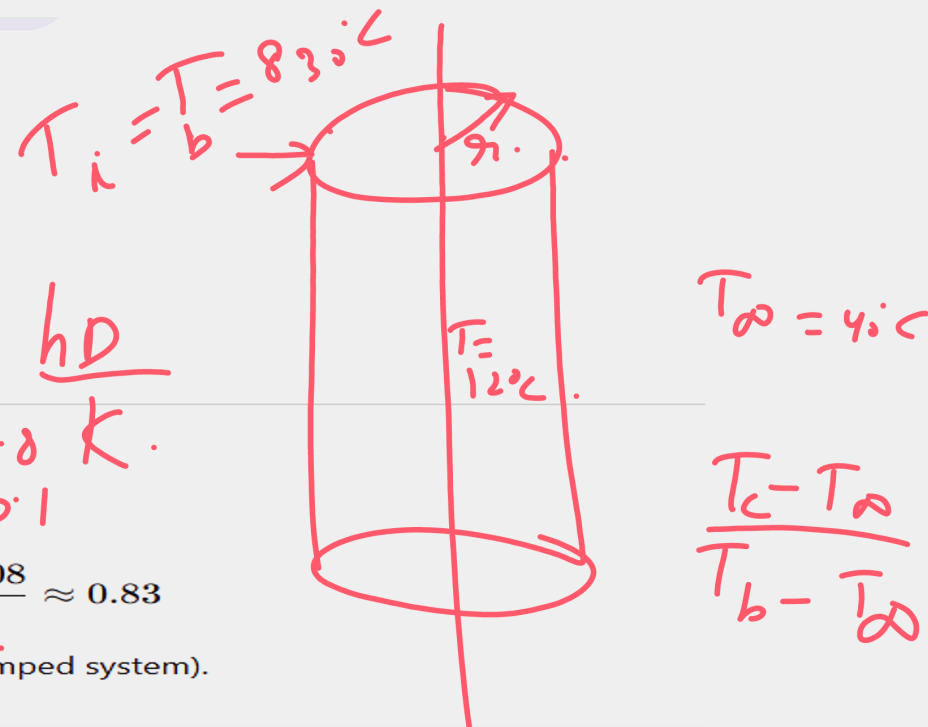
$$Bi = 0.83 > 0.1$$

$$Bi = \frac{180 \times 0.08}{17.4} \approx 0.83$$

☛ Since $Bi > 0.1$, Heisler charts are applicable (not lumped system).

Step 2: Dimensionless temperature at center

$$\theta^* = \frac{T_c - T_\infty}{T_i - T_\infty} = \frac{120 - 40}{830 - 40} = \frac{80}{790} \approx 0.101$$



CONDUCTIVE HEAT TRANSFER

Step 3: From Heisler Chart (Cylinder, centerline)

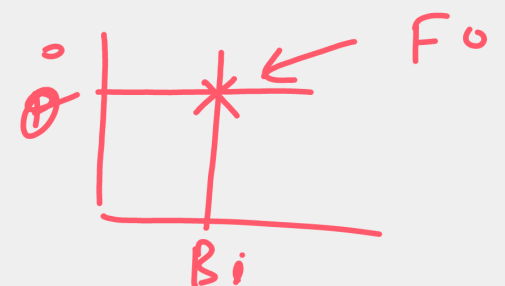
For:

• $Bi = 0.83$ ✓

• $\theta^* = 0.101$ ✓

From chart:

$Fo \approx 0.42$



Step 4: Time calculation

$$Fo = \frac{\alpha t}{r_0^2}$$

$$t = \frac{Fo \cdot r_0^2}{\alpha} = \frac{0.42 \times (0.08)^2}{5.28 \times 10^{-6}}$$

$$t \approx 509 \text{ s} \approx 8.5 \text{ minutes}$$

$$Fo = \frac{\alpha t}{L^2}$$

$$t = \frac{L^2 Fo}{\alpha}$$

CONDUCTIVE HEAT TRANSFER

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0.019/3600

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CONDUCTIVE HEAT TRANSFER

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For:

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CONDUCTIVE HEAT TRANSFER

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CONDUCTIVE HEAT TRANSFER

Step 5: Surface temperature

From Heisler Chart 2 (temperature distribution):

For:

- $Bi = 0.83$
- $Fo = 0.42$
- At surface ($r/r_0 = 1$)

So,

$$\frac{\theta_s}{\theta_c} \approx 0.42$$

$$\theta_s = 0.42 \times 0.101 = 0.0424$$

$$T_s = T_\infty + \theta_s(T_i - T_\infty)$$

$$T_s = 40 + 0.0424 \times 790 \approx 40 + 33.5 = 73.5^\circ C$$

$$\theta_s = \frac{T_s - T_\infty}{T_i - T_\infty}$$

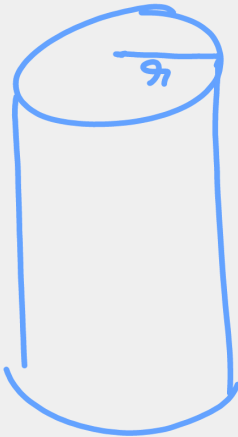
$$T_s = \theta_s(T_i - T_\infty) + T_\infty$$

CONDUCTIVE HEAT TRANSFER

Step 6: Temperature gradient at surface

Using convection boundary condition:

$$\left(\frac{dT}{dr} \right)_{r=r_0}$$



$$-k \left(\frac{dT}{dr} \right)_{r_0} = h(T_s - T_\infty)$$

$$\left(\frac{dT}{dr} \right)_{r_0} = -\frac{h}{k}(T_s - T_\infty)$$

$$= -\frac{180}{17.4}(74 - 40) =$$



$$Q = -kA \frac{dT}{dr_0}$$

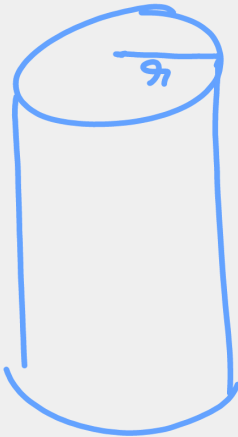
$$Q = hA \Delta T = h(T_s - T_\infty)$$

CONDUCTIVE HEAT TRANSFER

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$$\left(\frac{dT}{dr} \right)_{r_0} = -\frac{h}{k}(T_s - T_\infty)$$

$$= -\frac{180}{17.4}(74 - 40)$$

$$= \underline{\underline{351.33}}$$

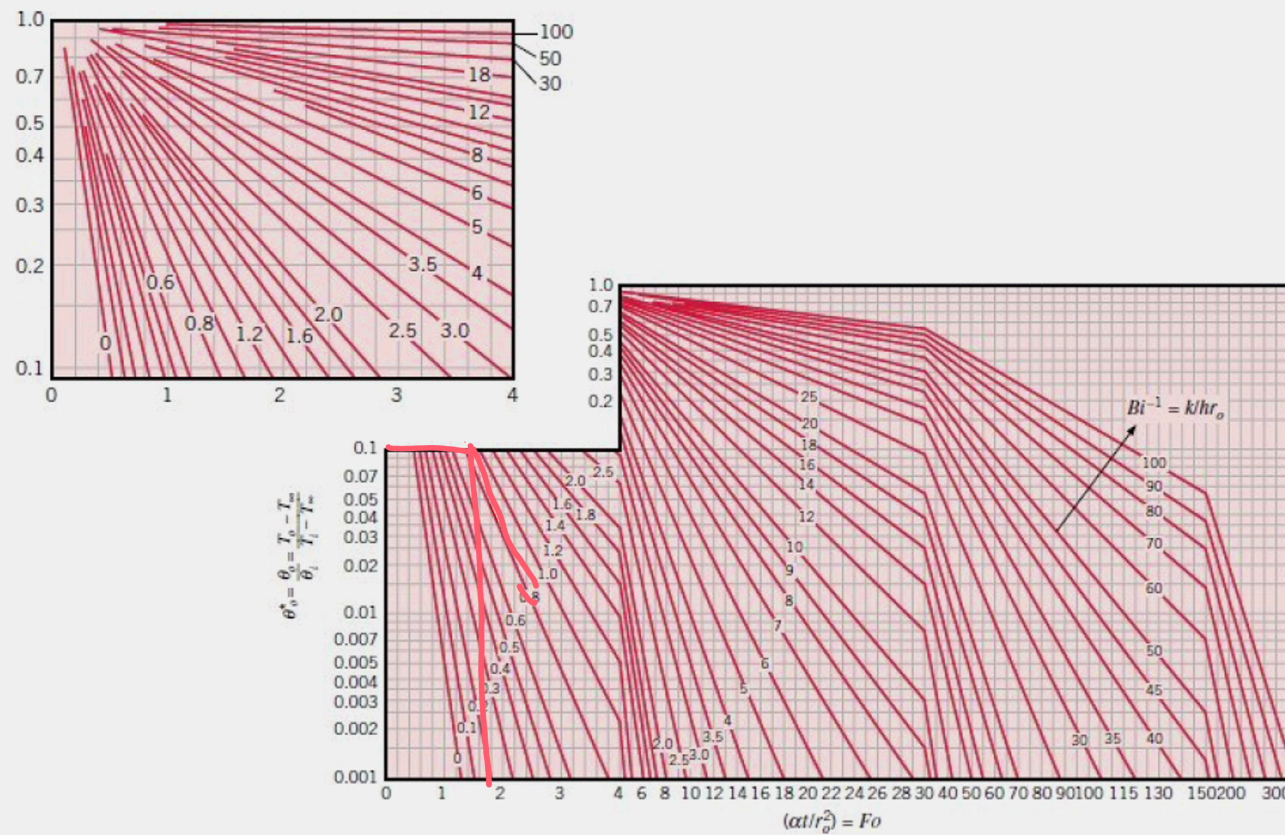
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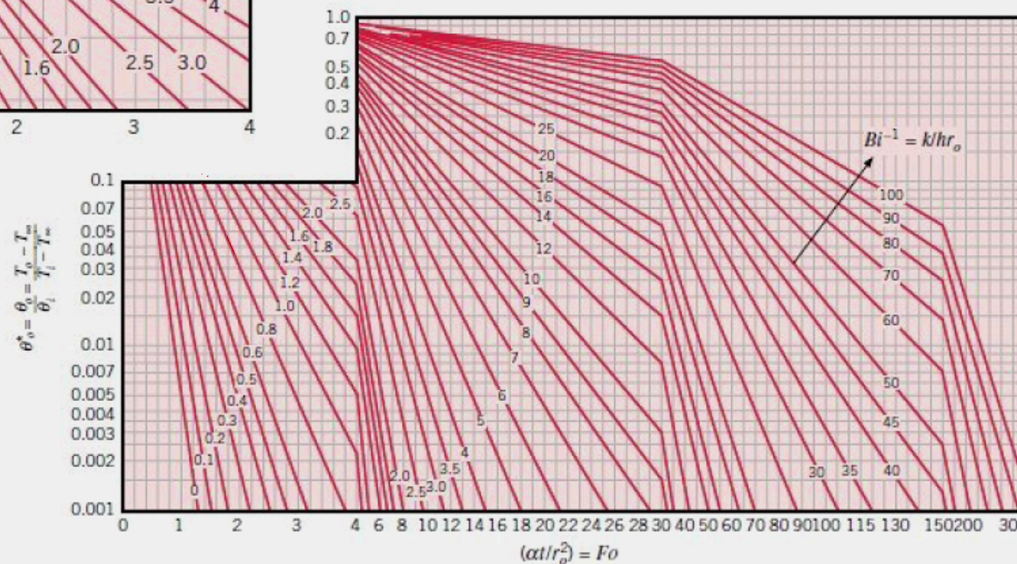
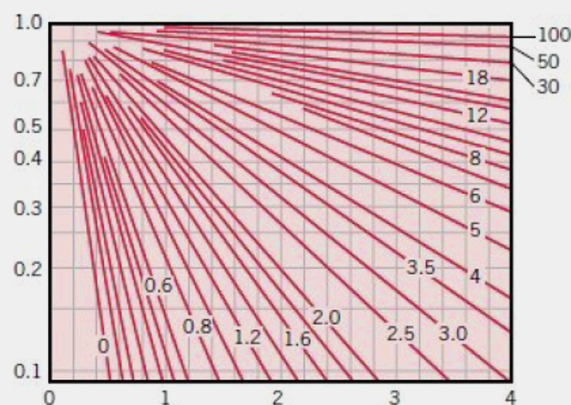
CONDUCTIVE HEAT TRANSFER

The cylinder:



CONDUCTIVE HEAT TRANSFER

The cylinder:



Transient

$Bi < 0.1$
lumped parameter

$Bi > 0.1$
Heisler Chart

CONDUCTIVE HEAT TRANSFER

10. The Heisler charts are used to solve problems involving:

- A) Steady-state conduction in complex geometries
- B) Forced convection over cylinders
- C) Transient heat conduction with $Bi > 0.1$ ✓
- D) Radiation exchange between non-grey surfaces

11. Numerical: A fin will be effective in enhancing heat transfer only if the term

$(hP/kA)^{1/2}$ is: A) Large B) Small C) Equal to 1 D) Zero

CONVECTIVE HEAT TRANSFER

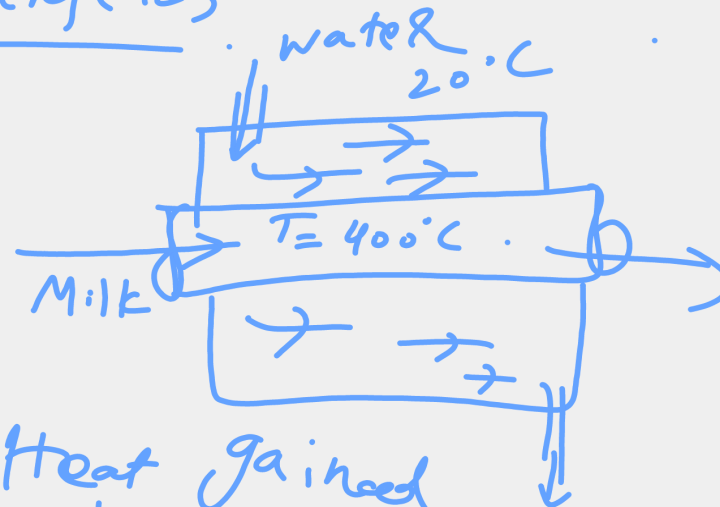
Heat Exchangers

Pasteurization

Double pipe H.x

Heat lost
by Milk =

Heat gained
by Water.



Fins

Extended
Surface

CONVECTIVE HEAT TRANSFER

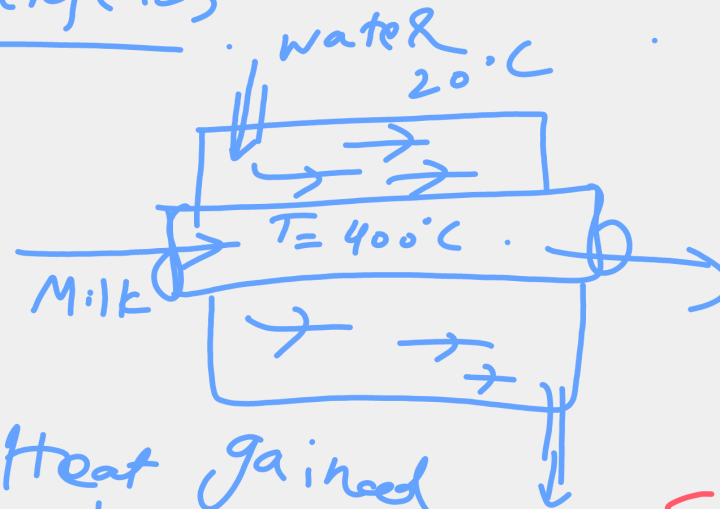
Heat Exchangers

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Fins
Extended Surface

→ Energy balance

CONVECTIVE HEAT TRANSFER

$$Q_{\text{lost by Mik}} = Q_{\text{gain by water}}$$

$$m_m c_{p_m} (T_{hi} - T_{ho}) = m_w c_{p_w} (T_{co} - T_{ci})$$

→ To find
one of the Temp

(or) mass flow rate → kg/s.

Sensible heat

$$Q = m c dT$$

→ ①

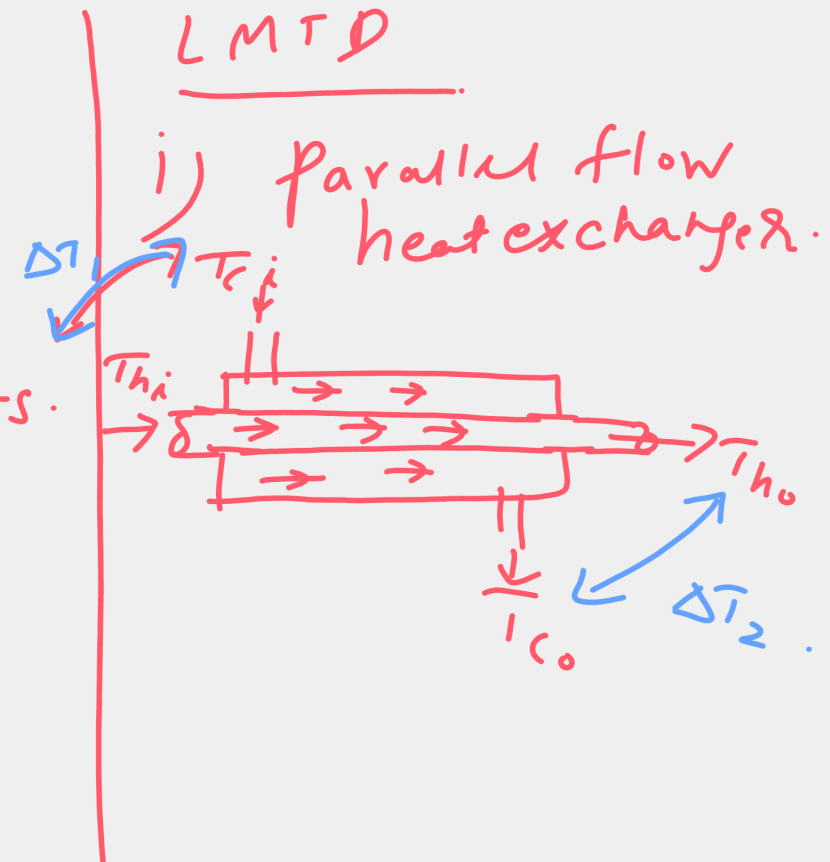
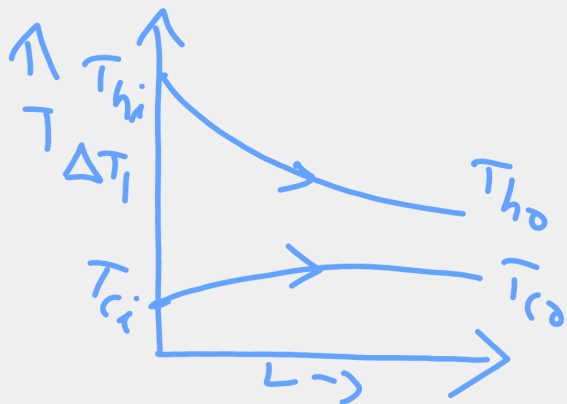
CONVECTIVE HEAT TRANSFER

i) LMTD, NTU

LMTD $\rightarrow$ logarithmic Mean Temp diff.

NTU $\rightarrow$ Number of transfer units.

$$LMTD = \frac{\Delta T_1 - \Delta T_2}{\ln \left(\frac{\Delta T_1}{\Delta T_2} \right)}$$



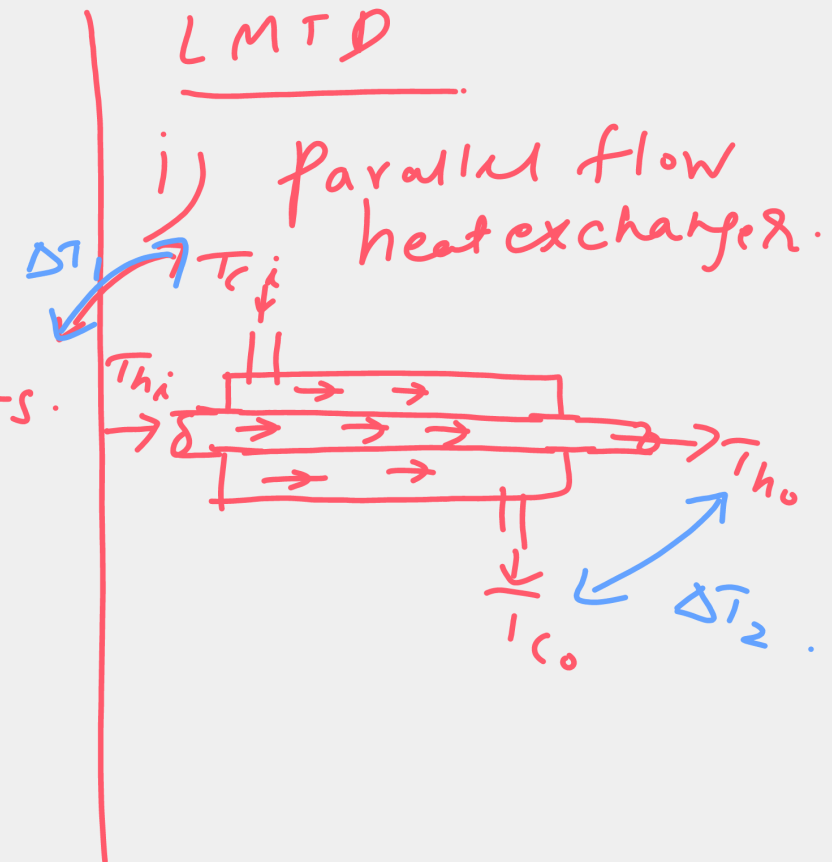
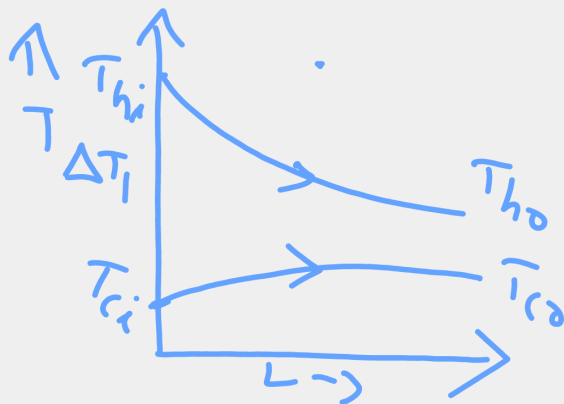
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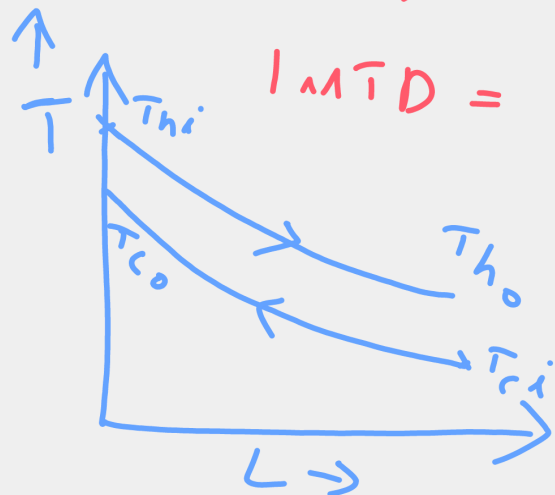


CONVECTIVE HEAT TRANSFER

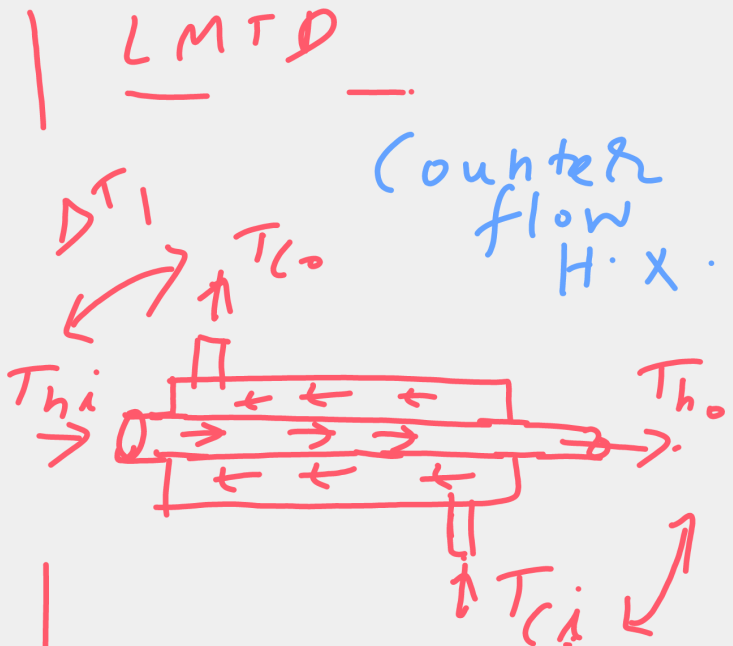
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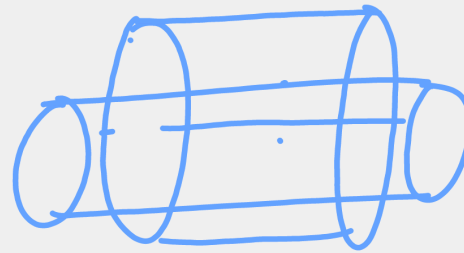
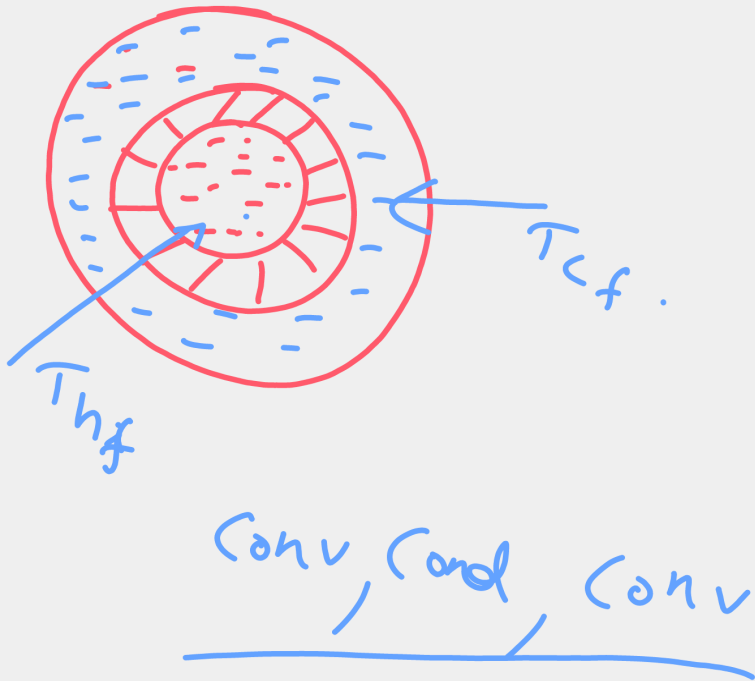
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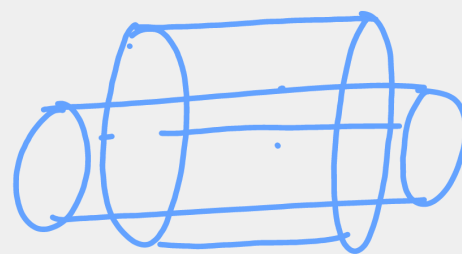
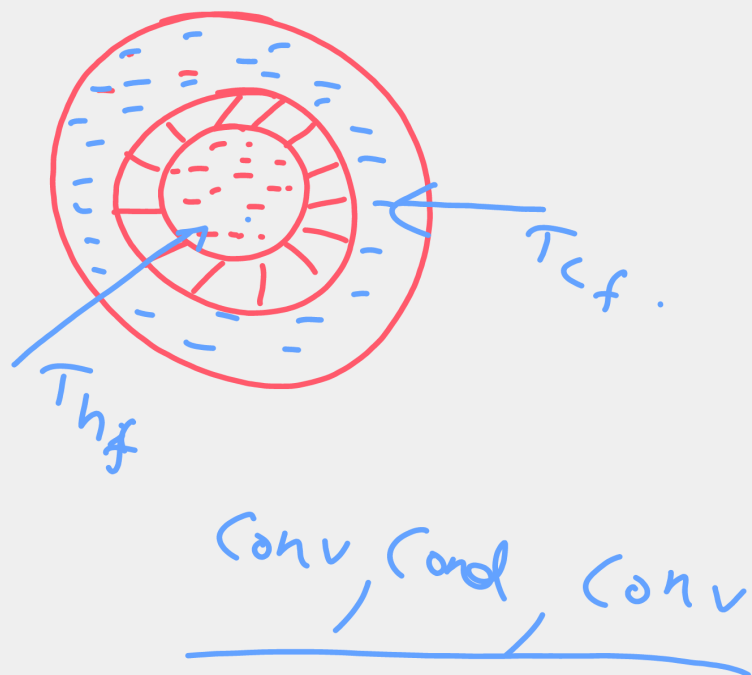
$$\Delta T_1 = T_{hi} - T_{co}$$

$$\Delta T_2 = T_{ho} - T_{ci}$$

CONVECTIVE HEAT TRANSFER



CONVECTIVE HEAT TRANSFER



$$\text{Effectiveness } (\epsilon) = \frac{Q_{act}}{Q_{max}} = \frac{Q_{act}}{Q_{theor.}}$$

CONDUCTIVE HEAT TRANSFER

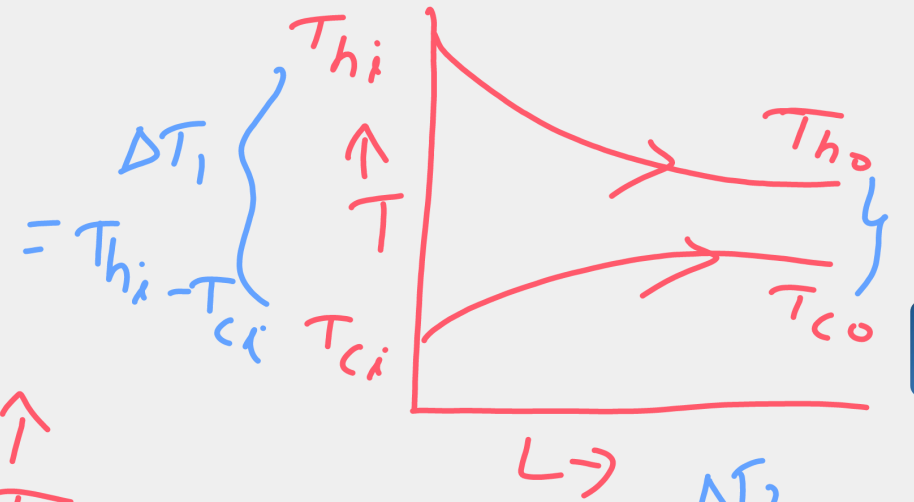
$$\begin{array}{l} Q_{\text{lost}} \\ \text{hot} \\ \text{body} \end{array} = \begin{array}{l} Q \\ \text{gained} \\ \text{by} \\ \text{the cold} \\ \text{body.} \end{array}$$
$$\begin{array}{c} \uparrow \\ m_h c_p (T_{hi} - T_{ho}) \end{array} = \begin{array}{c} \uparrow \\ m_c c_p (T_{co} - T_{ci}) \end{array}$$

$\underbrace{m_h}_{?} = ?$

CONDUCTIVE HEAT TRANSFER

$Q_{\text{lost hot body}} =$

$Q_{\text{gained by the cold body.}}$



$$m_h c_{p_h} (T_{h_i} - T_{h_o}) = m_c c_{p_c} (T_{c_o} - T_{c_i})$$

$m_h = ?$

$$LMTD = \frac{\Delta T_1 - \Delta T_2}{\ln \left(\frac{\Delta T_1}{\Delta T_2} \right)}$$



CONDUCTIVE HEAT TRANSFER

Calculate Effectiveness (ϵ) & $H \cdot x$.



CONDUCTIVE HEAT TRANSFER

Calculate Effectiveness (ϵ) & $H \cdot x$.

$Bi < 0.1$,
lumped.

$$\frac{Bi = 0.1}{\frac{R_{\text{cond}}}{R_{\text{conv}}} = 0.1}$$

$Bi > 0.1$
Heisler
Chart.

$Bi \rightarrow$

Fourier
Number $Fo = \frac{\alpha t}{L^2} .$

} unsteady
State
(or)
transient cond.



CONDUCTIVE HEAT TRANSFER

Calculate Effectiveness (ϵ) & $H \cdot x$.

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CONDUCTIVE HEAT TRANSFER

Calculate Effectiveness (ϵ) & $H \cdot x$.

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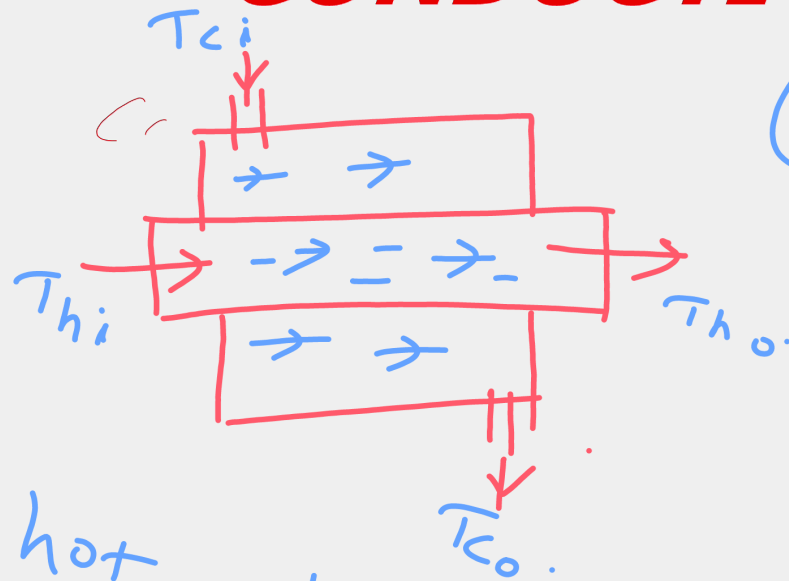
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CONDUCTIVE HEAT TRANSFER



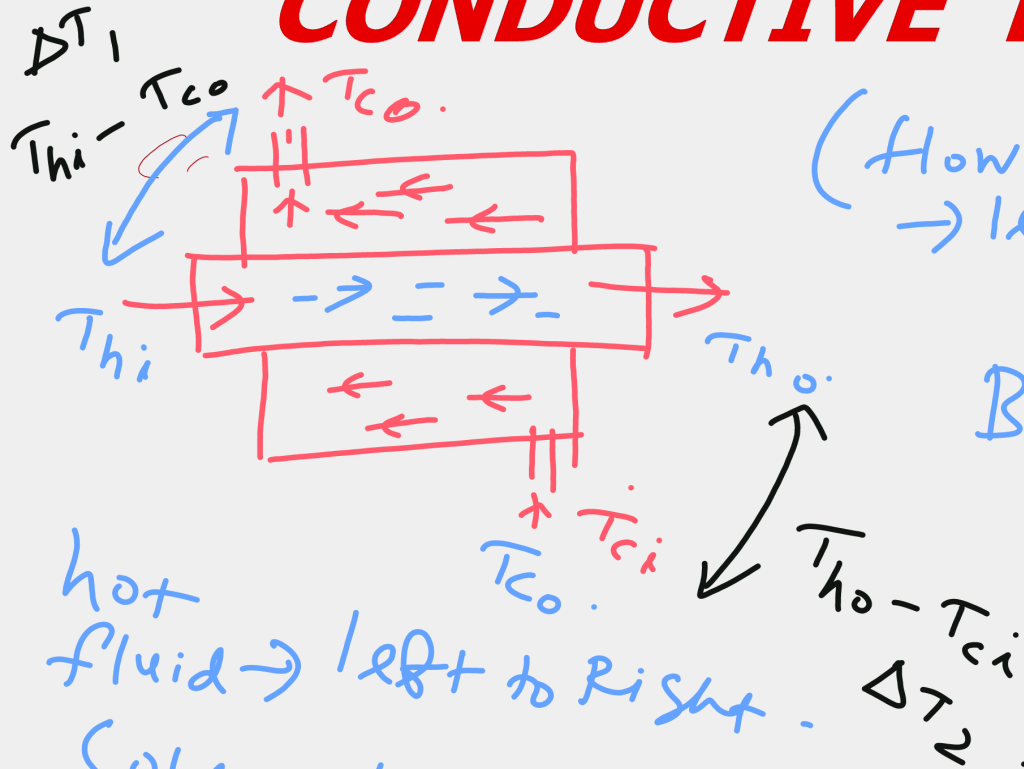
(flow
→ left to right).

Both fluids flow
in same direction
→ parallel flow

hot
fluid → left to right.

cold
fluid → left to right.

CONDUCTIVE HEAT TRANSFER



(flow
→ left to right).

Both fluids flow
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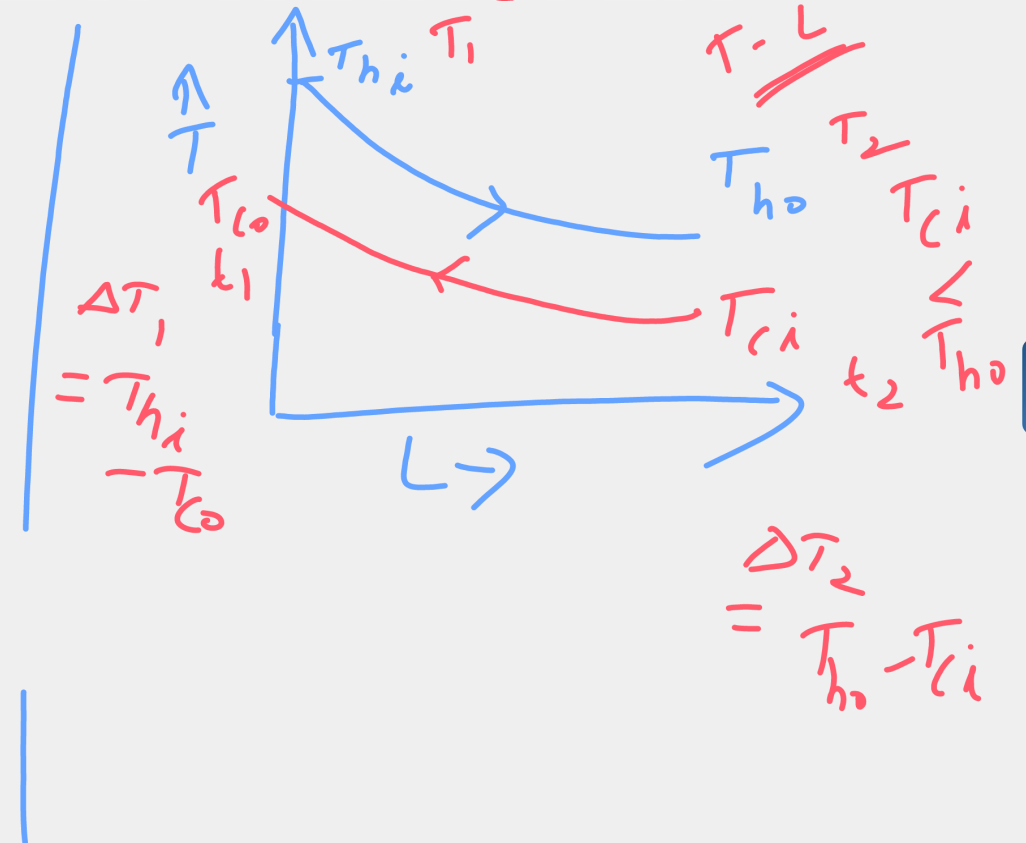
hot
fluid → left to right.

cold
fluid → left to right.

CONDUCTIVE HEAT TRANSFER

$$C. LMTD = \frac{(T_{hi} - T_{co}) - (T_{ho} - T_{ci})}{\ln \left(\frac{T_{hi} - T_{co}}{T_{ho} - T_{ci}} \right)}$$

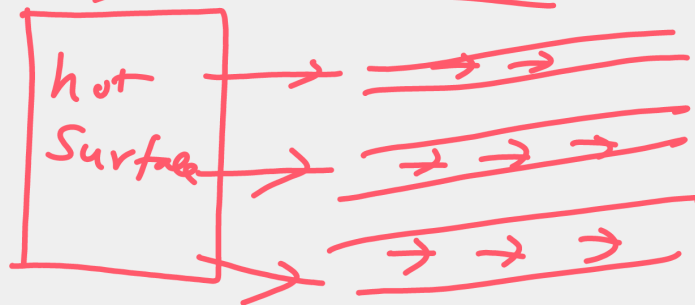
$$= \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln \left(\frac{T_1 - t_2}{T_2 - t_1} \right)}$$



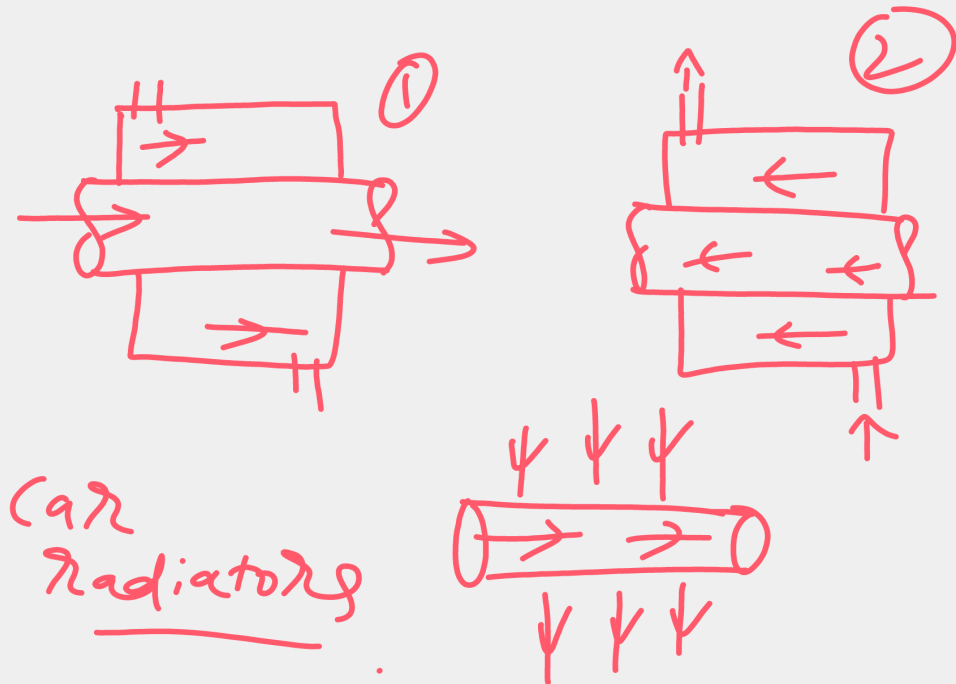
CONDUCTIVE HEAT TRANSFER

Type of H.T

- i) Parallel flow
- ii) Counter flow
- iii) Cross flow $\rightarrow$



car radiators





CONDUCTIVE HEAT TRANSFER

Cr Analytical Method $\rightarrow$ LMTD, NTU.

Graphical Method.

NTU $\rightarrow$ Number of Transfer units.

$U \rightarrow$ Overall heat trans. Coeff.

$$NTU = \frac{UA}{C_{min.}}$$

CONDUCTIVE HEAT TRANSFER

C- Analytical Method $\rightarrow$ LMTD, NTU.

Graphical Method.

NTU $\rightarrow$ Number of Transfer units.

$U \rightarrow$ Overall heat trans. Coeff.
 $A \rightarrow$ Area of H.x.

$NTU = \frac{UA}{C_{min.}}$

Combined term.

$$\frac{1}{U} = \frac{1}{h_c} + \frac{1}{h_h}$$

CONDUCTIVE HEAT TRANSFER

$$Q_{\text{lost by hot fluid}} = Q_{\text{gained by cold fluid}}$$

$$\underbrace{m_h c_p}_{C_h} (T_{hi} - T_{ho}) = \underbrace{m_c c_p}_{C_c} (T_{co} - T_{ci})$$

Calculate both C_h, C_c .

$$C_h = m_h c_{ph} = 2000 \frac{\text{kg}}{\text{s}} \times 2.2 \frac{\text{J}}{\text{kgK}}$$

$$C_c = m_c c_{pc} = 800 \times 4.187$$

CONDUCTIVE HEAT TRANSFER

$$Q_{\text{lost by hot fluid}} = Q_{\text{gained by cold fluid}}$$

$$\underbrace{m_h c_p}_{C_h} (T_{hi} - T_{ho}) = \underbrace{m_c c_p}_{C_c} (T_{co} - T_{ci})$$

$$C_h > C_c \therefore C_c$$

(or) $C_{min} = \min(C_c, C_h)$

Calculate both C_h, C_c .

$$\begin{aligned} C_h &= m_h c_{ph} \\ &= 2000 \frac{\text{kg}}{\text{s}} \times 2.2 \frac{\text{J}}{\text{kgK}} \\ &= 4400 \end{aligned}$$

$$\begin{aligned} C_c &= m_c c_{pc} \\ &= 800 \times 4.187 \\ &= 3349.6 \end{aligned}$$



CONDUCTIVE HEAT TRANSFER

C.

$$NTU = \frac{UA}{\underline{C_{min}}}$$

NTU, LMTD

CONDUCTIVE HEAT TRANSFER

Boiling

→ Nucleate pool.
→ flow boiling.

NTU, LMTD

$\epsilon < 1$ (0-1)

Condensation

Engine → Efficiency
Refrigerator → C.O.P.

Heat Exchanger → Effectiveness (ϵ).

Boiling
Condensation
are phase
change.



CONDUCTIVE HEAT TRANSFER

Cr

In H.x

$$\Delta T_1 = \Delta T_2 = 8.$$

Find LMTD = $(\Delta T)_{lm}$

$$Ans = \Delta T_1 = \Delta T_2 = (\Delta T)_{lm} = 8.$$



CONDUCTIVE HEAT TRANSFER

Cr

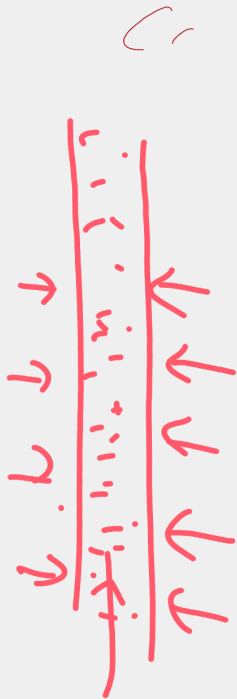
In H.x

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$$\text{Ans} = \Delta T_1 = \Delta T_2 = (\Delta T)_{lm} = 8.$$

CONDUCTIVE HEAT TRANSFER



In H.X

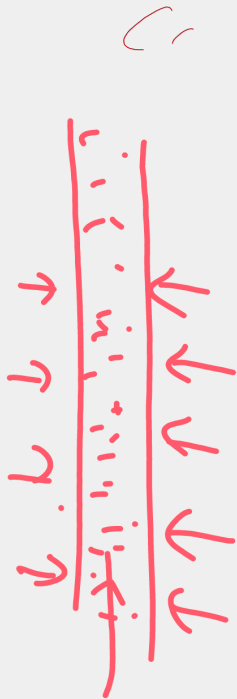
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CONDUCTIVE HEAT TRANSFER



In H.X

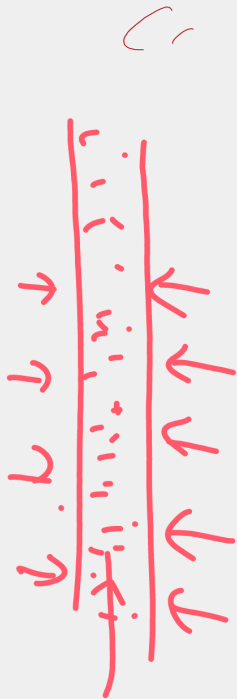
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CONDUCTIVE HEAT TRANSFER



In H.X

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