Heat Transfer

- Heat transfer - movement of energy due to a temperature difference
- Can only occur if a temperature difference exists
- Occurs through:
  1. conduction,
  2. convection, and
  3. radiation, or
  4. combination of above
Heat Transfer

• May be indicated as total transfer

• Identified by total heat flow (Q) with units of Btu

• Identified by rate of heat flow (q) or $\Delta Q/\Delta t$ with units of watts or Btu/hr

• Also, may be expressed as heat transfer per unit area = heat flux or q/A

Heat Transfer

• Heat transfer may be classified as:
  1. Steady-state:
     o all factors are stabilized with respect to time
     o temperatures are constant at all locations
     o steady-state is sometimes assumed if little error results
  2. Unsteady-state (transient) heat transfer occurs when:
     o temperature changes with time
     o thermal processing of foods is an important example
     o must know time required for the coldest spot in can to reach set temperature
CONDUCTION HEAT TRANSFER

- Occurs when heat moves through a material (usually solid or viscous liquid) due to molecular action only
- Heat/energy is transferred at molecular level
- No physical movement of material
- Heating/cooling of solid
- Heat flux is directly proportional to the temperature gradient, and inversely proportional to distance (thickness of material).

CONDUCTION HEAT TRANSFER

- May occur simultaneously in one, or two, or three directions
- Many practical problems involve heat flow in only one or two directions
- Conduction along a rod heated at one end is an example of two-dimensional conduction
- Heat flows along the length of the rod to the cooler end (one direction)
- If rod is not insulated, heat is also lost to surroundings
- Center warmer than outer surface
One dimensional conduction heat transfer is a function of:
1. temperature difference,
2. material thickness,
3. area through which heat flows, and
4. resistance of the material to heat flow

Fourier’s Law Of Heat Conduction:

\[
\frac{\Delta Q}{\Delta t} = q_x = -kA \frac{dT}{dx}
\]

\(\Delta Q\) = Total heat flow
\(q_x\) = rate of heat flow in x direction by conduction, W
\(k\) = thermal conductivity, W/m°C
\(A\) = area (normal to x-direction) through which heat flows, m²
\(T\) = temperature, C
\(x\) = distance increment, variable, m
SIGN CONVENTION

Equation

For the formulas to work, we must keep the signs straight and be aware of what direction we mean as being positive.

\[ \frac{\Delta Q}{\Delta t} = -kA \frac{\Delta T}{\Delta x} \]

Note: the thickness \( L \) of the body is now expressed in terms of an interval \( \Delta x \) on the \( x \) axis.

If the differences \( \Delta \) are made very small, then we have:

\[ \frac{dQ}{dt} = -kA \frac{dT}{dx} \]

Note: This equation is more general and may apply to non-uniform cross-sections (e.g., varying \( A \) or \( L \)).

Consider these two possibilities:

Case 1. Hot \( T_1 \) - Cold \( T_2 \)

This is a "negative" slope since \( T_2 - T_1 \) is negative

Case 2. Cold \( T_1 \) - Hot \( T_2 \)

This is a "positive" slope since \( T_2 - T_1 \) is positive

Positive \( x \) direction

What is \( k \)?
USING FOURIER’S LAW

\[ q_x = -kA \frac{dT}{dx} \]

BC:
\[ x = x_1 \rightarrow T = T_1 \]
\[ x = x_2 \rightarrow T = T_2 \]

\[ q_x \frac{dx}{A} = -kdT \]

Integrating:
\[ \int_{x_1}^{x} q_x \frac{dx}{A} = - \int_{T_1}^{T} kdT \]
\[ q_x \frac{x - x_1}{A} = -k(T - T_2) \]
\[ T = T_1 - \frac{q_1}{kA} (x - x_1) \]
\[ q_x = -kA \frac{T - T_1}{(X - X_1)} \]

HEAT CONDUCTION IN MULTILAYERED SYSTEMS

Composite Rectangular Wall (In Series)

\[ k_A \quad k_B \quad k_C \]

Temperature profile in a multilayered system
USING FOURIER'S LAW:

\[ q = -kA \frac{dT}{dX} \]

\[ \Delta T = -q \frac{\Delta x}{kA} \]

\[ \Delta T_A = -q \frac{\Delta x_A}{k_A A} \]

\[ \Delta T_B = -q \frac{\Delta x_B}{k_B A} \]

\[ \Delta T_C = -q \frac{\Delta x_C}{k_C A} \]

\[ \Delta T = T_1 - T_2 \]

\[ \Delta T = \Delta T_A + \Delta T_B + \Delta T_C \]

\[ T_1 - T_2 = -\frac{q}{A} \left( \frac{\Delta X_A}{k_A} + \frac{\Delta X_B}{k_B} + \frac{\Delta X_C}{k_C} \right) \]

\[ \Delta T_A = -q \frac{\Delta x_A}{k_A A} \]

\[ \Delta T_B = -q \frac{\Delta x_B}{k_B A} \]

\[ \Delta T_C = -q \frac{\Delta x_C}{k_C A} \]
CONDUCTION IN CYLINDRICAL OBJECTS

Fourier’s law in cylindrical coordinates

\[ q_r = -kA \frac{dT}{dr} \]

\[ q_r = -k \cdot 2 \pi r \cdot L \frac{dT}{dr} \]

Boundary Conditions:

\[ T = T_i \quad \text{at} \quad r = r_i \]

\[ T = T_o \quad \text{at} \quad r = r_o \]

Integrating:

\[ q = \frac{q}{2\pi L} \int_{r_i}^{r_o} \frac{dT}{dr} \]

\[ q = -k \int_{r_i}^{T_o} dT \]

\[ q = \left( \frac{2\pi Lk(T_i - T_o)}{\ln\left(\frac{r_o}{r_i}\right)} \right) \]

COMPOSITE CYLINDRICAL TUBE

FROM FOURIER’S LAW:

\[ q_r = \frac{2\pi Lk(T_i - T_o)}{\ln\left(\frac{r_o}{r_i}\right)} \]
Let us define logarithmic mean area $A_m$ such that

$$A = \frac{q_r}{kA_m} \left( \frac{T_1 - T_o}{r_o - r_i} \right)$$

where

$$A_m = 2\pi L \left( \frac{r_o - r_i}{\ln \left( \frac{r_o}{r_i} \right)} \right)$$

and

$$T_i - T_o = \frac{q_r (r_o - r_i)}{kA_m}$$

$$T_1 - T_2 = \frac{q_r (r_2 - r_1)}{(kA_m)_{12}}$$

$$T_2 - T_3 = \frac{q_r (r_3 - r_2)}{(kA_m)_{23}}$$

Adding the above two equations,

$$q_r = \frac{\Delta r}{kA_m} \left( \frac{1}{(kA_m)_{12}} + \frac{1}{(kA_m)_{23}} \right)$$

---

**Convection Heat Transfer**

- **Transfer** of energy due to the movement of a heated fluid
- **Movement** of the fluid (liquid or gas) causes transfer of heat from regions of warm fluid to cooler regions in the fluid
- **Natural Convection** occurs when a fluid is heated and moves due to the change in density of the heated fluid
- **Forced Convection** occurs when the fluid is moved by other methods (pumps, fans, etc.)
CONVECTIVE HEAT TRANSFER: heat transfer to fluid

\[ q = h A(T_s - T_a) \]

- \( q \) = rate of heat transfer
- \( h \) = convective heat transfer coefficient, W/m\(^2\).\(^\circ\)C
- \( T_s \) = surface temperature
- \( T_a \) = surrounding fluid temperature

Fluid absorbs heat (temperature increase: density decrease)
Colder fluid (higher density)
Fluid absorbs heat (temperature increase: density decrease)
FLUID FLOW IN A PIPE

Fluid flow can occur as
- laminar flow
- turbulent flow
- transition between laminar and turbulent flow
- direction of flow —> parallel or perpendicular to the solid object

HEAT TRANSFER TO FLUID

\[ q = h A (T_s - T_a) \]

\[ h = f (\text{density, velocity, diameter, viscosity, specific heat, thermal conductivity, viscosity of fluid at wall temperature}) \]

- The convective heat transfer coefficient is determined by dimensional analysis.
- A series of experiment are conducted to determine relationships between following dimensionless numbers.
HEAT TRANSFER TO FLUID

Dimensionless Numbers In Convective Heat Transfer

Nusselt Number = \( N_{nu} = \frac{hD}{k} \)
Prandtl Number = \( N_{Pr} = \frac{\mu C_p}{k} \)
Reynolds Number = \( Re = \frac{(\rho v D)}{\mu} \)

Where
- \( D \) = characteristic dimension
- \( k \) = thermal conductivity of fluid
- \( v \) = velocity of fluid
- \( C_p \) = specific heat of fluid
- \( \rho \) = density of fluid
- \( \mu \) = viscosity of fluid

HEAT TRANSFER TO FLUID ....> h?

\[ N_{Nu} = f \left( N_{Re}, N_{Pr} \right) \]

Laminar flow in pipes: If \( N_{Re} < 2100 \)
For \( \left( N_{Re} \times N_{Pr} \times \frac{D}{L} \right) < 100 \)
\[ N_{Nu} = 3.66 + \frac{0.085 \left( N_{Re} \times N_{Pr} \times \frac{D}{L} \right)}{1 + 0.045 \left( N_{Re} \times N_{Pr} \times \frac{D}{L} \right)^{0.66}} \left( \frac{\mu_b}{\mu_w} \right)^{0.14} \]

For \( \left( N_{Re} \times N_{Pr} \times \frac{D}{L} \right) > 100 \)
\[ N_{Nu} = 1.86 \left( N_{Re} \times N_{Pr} \times \frac{D}{L} \right)^{0.33} \left( \frac{\mu_b}{\mu_w} \right)^{0.14} \]

All physical properties are evaluated at bulk fluid temperature, except \( m_w \)
Transition Flow in Pipes \( \rightarrow \) \( N_{RE} \) between 2100 and 10,000:

- use chart to determine \( h \):
- diagram J Colburn factor (\( J \)) vs Re.

\[
J = \frac{h}{\rho c_p V} \left( \frac{C_p \mu}{k} \right)^{\frac{3}{2}} \left( \frac{\mu_B}{\mu} \right)^{0.036}
\]

Turbulent Flow in Pipes \( \rightarrow \) \( N_{RE} > 10,000 \):

\[
N_{NU} = 0.023 N_{Pr}^{0.33} \left( \frac{\mu_B}{\mu_w} \right)^{0.14}
\]
HEAT TRANSFER TO FLUID \rightarrow FREE CONVECTION

Free convection involves the dimensionless number called Grashof Number, \( N_{Gr} \)

\[
N_{Gr} = \left( \frac{D^3 \beta \rho g \Delta T}{m^2} \right)
\]

\[
N_{Nu} = \left( \frac{h D}{k} \right) = a \left( N_{Gr} \right)^m \left( N_{Pr} \right)^n
\]

\( \beta = \text{koeff ekspansi volumetrik (koef muai volumetrik; 1/K)} \)

All physical properties are evaluated at the film temperature \( \rightarrow T_f = (T_w + T_b)/2 \)

Value of \( a \) and \( m \) = f(physical configuration)

- **Vertical surface**
  - \( D = \text{vertical dim.} < 1 \)
  - \( m N_{Gr} N_{Pr} < 10^4 \)
  - \( a = 1.36 \)
  - \( m = 1/5 \)

- **Horizontal cylinder**
  - \( D = \text{dia} < 20 \text{ cm} \)
  - \( N_{Gr} N_{Pr} < 10^{-5} \)
  - \( a = 0.49 \)
  - \( m = 0 \)
  - \( 10^{-5} < N_{Gr} N_{Pr} < 1 \)
  - \( a = 0.71 \)
  - \( m = 1/25 \)
  - \( 1 < N_{Gr} N_{Pr} < 10^{-4} \)
  - \( a = 1.09 \)
  - \( m = 1/10 \)

- **Horizontal flat surface**
  - **Facing Upward**
    - \( 10^5 < N_{Gr} N_{Pr} < 2 \times 10^7 \)
    - \( a = 0.54 \)
    - \( m = 1/4 \)
  - **Facing downward**
    - \( 2 \times 10^7 < N_{Gr} N_{Pr} < 3 \times 10^{10} \)
    - \( a = 0.14 \)
    - \( m = 1/3 \)

phariyadi.staff.ipb.ac.id \quad -- \quad ITP530
Temperature profile: conductive and convective heat transfer through a slab

\[ Q = UA(T_a - T_b) \]

where

\[ U = \text{Overall heat transfer coefficient} \ [= \text{W/m}^2\text{C}] \]

Steady State:

\[ q_i = q_x = q_o = q \]
\[ q = UA(T_a - T_b) \]
\[ q_i = q = h_i A (T_s - T_1) \]
\[ q_x = q = k A (T_1 - T_2) / \Delta x \]
\[ q_o = q = h_o A (T_2 - T_b) \]
\[ T_a - T_b = (T_a - T_1) + (T_1 - T_2) + (T_2 - T_b) \]

\[ \frac{q}{U} = \frac{q}{h_i A} + \frac{q \Delta x}{k A} + \frac{q}{h_o A} \]

\[ \frac{1}{U} = \frac{1}{h_i A} + \frac{\Delta x}{k A} + \frac{1}{h_o A} \]

Atau, umum:

\[ \frac{1}{U_i A_i} = \frac{1}{h_i A_i} + \frac{\Delta x}{k A_{im}} + \frac{1}{h_o A_o} \]

\[ A_i = A_{im} = A_o = A \]
HEAT TRANSFER TO FLUID \rightarrow U?

Surrounding fluid temp; \( T_b < T_a \)

\[
\frac{1}{U} = \frac{1}{h_i} + \frac{\Delta r}{k} + \frac{1}{h_o}
\]

Atau, umum:

\[
\frac{1}{U} = \frac{1}{h_i A_i} + \frac{\Delta r}{k A_{im}} + \frac{1}{h_o A_o}
\]

\[
A_{im} = \frac{A_o - A_i}{\ln \frac{A_o}{A_i}}
\]

Thermal Radiation

The transfer of energy by electromagnetic waves in the thermal range

Electro- what??:

electromagnetic spectrum

Infrared

0.76 \( \mu \)m

Visible

0.38 \( \mu \)m

Ultra violet

Let us call energy transferred by electromagnetic radiation: "Radiant energy"

Thermal radiation is in the range 0.1 to 100 \( \mu \)m.
Absorption

When radiant energy coming from a source falls on a body, part of it is absorbed, part of it may be reflected, and part transmitted through it.

\[ \text{Absorptivity} + \text{Reflectivity} + \text{Transmittivity} = 1 \]

\[ \frac{\text{fraction absorbed}}{A} \quad \frac{\text{fraction reflected}}{R} \quad \frac{\text{fraction transmitted}}{T} \]

Emission

Today's headline: Scientists discover that any body whose temperature is above absolute zero emits radiant energy according to the Stefan-Boltzmann law.

\[ \dot{Q}_e = \sigma A T^4 \]

\( \sigma \) is the emissivity of surface (ranging between 0 and 1) and depends on:
- nature of surface
- temperature of surface
- wavelength of the radiation being emitted or absorbed

<table>
<thead>
<tr>
<th>Material</th>
<th>( e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polished aluminum</td>
<td>0.055</td>
</tr>
<tr>
<td>Oxidized aluminum</td>
<td>0.26</td>
</tr>
<tr>
<td>Water</td>
<td>0.066</td>
</tr>
<tr>
<td>&quot;Black Body&quot;</td>
<td>1.0</td>
</tr>
</tbody>
</table>

\( e \) indicates how well a body emits or absorbs radiant energy. A good emitter is a good absorber, and vice versa.

At any particular wavelength, the emissivity = absorptivity.
**Kirchhoff's radiation law**

The thermal range covers wavelengths from 0.1 to 100 μm.

100 μm | thermal range | 0.1 μm

Now, the emissivity of a surface depends on the wavelength of the radiation being emitted or absorbed. A surface whose emissivity is 0.8 at 10 μm may have an emissivity of only 0.1 at 100 μm. This is called a “selective surface.”

**Absorption & Emission**

1. The fraction of energy absorbed (oQ) is converted to internal energy (U) and thus is equivalent to heat flow having taken place. The temperature of the body thus rises (if no change of state).

2. But, all bodies above absolute zero emit radiant energy and the rate of emission increases as the temperature of the body rises (Stefan-Boltzmann law).

3. Thus, if no conduction or convection or any other energy input, then the temperature of the body rises until the rate of emission becomes equal to the rate of absorption. - Radiative (dynamic) equilibrium

If this didn't happen, the entire body would continue to absorb radiation and the temperature would rise indefinitely till melt down.
Radiative heat transfer

1. Suppose the surroundings are maintained at a low temperature $T_1$ and the body is maintained at a higher temperature $T_2$.

2. All bodies simultaneously emit and absorb radiant energy from the surroundings.

3. The rate of emission from the body is given by $\dot{Q}_e = \varepsilon\sigma T_2^4$.

4. The rate of absorption by the body is given by $\dot{Q}_a = \alpha\dot{Q}$, and depends on:
   - the temperature of the surroundings
   - the emissivity or absorptance of the body, since $\alpha = \varepsilon$

Summary:
- Incident on body: $\dot{Q}_i = \varepsilon_1\sigma T_1^4$
- Absorbed by body: $\dot{Q}_a = \alpha\dot{Q}_i$
  - $\dot{Q}_a = \varepsilon_2\sigma T_1^4$
  - $\dot{Q}_a = \varepsilon_2\sigma T_2^4$
- Emitted by body: $\dot{Q}_e = \varepsilon\sigma T_2^4$

---

Radiative heat transfer

Consider the energy flow into and out from the body:

- Electrical energy in $\dot{Q}_i$
- Radiation emitted $\dot{Q}_e = \varepsilon\sigma T_2^4$
- Radiation absorbed $\dot{Q}_a = \alpha\dot{Q}_i$

At radiative dynamic equilibrium, $\text{ENERGY OUT} = \text{ENERGY IN}$

- Radiant energy emitted $\dot{Q}_e$
- Radiant energy absorbed $\dot{Q}_a$

This quantity represents the net heat flow $\Delta Q$ from the body and is equal to the rate of electrical energy that must be supplied to maintain the body at $T_2$:

$\Delta Q = \varepsilon\sigma T_2^4 - \varepsilon_1\sigma T_1^4$

If the surroundings have an emissivity of $1$, then $\varepsilon_1 = 1$, then we have:

$\Delta Q = \varepsilon_2\sigma A (T_2^4 - T_1^4)$

Net Heat flow out (in this case indicates net radiant heat flow from the body and transfer of internal energy from body to surroundings).

Temperature of surroundings

Temperature of body
TRANSIENT (UNSTEADY-STATE) HEAT TRANSFER

**Rate of cooling**

**Question:** If heat flows from a body (by conduction) and the body cools, what is the rate at which the temperature of the body changes ($\frac{dT}{dt}$)?

**Answer:** Start with heat capacity formula:

$$\Delta Q = mc\Delta T$$

Differentiate w.r.t. time to get (assuming no change of state)

$$\frac{dQ}{dt} = mc \frac{dT}{dt}$$

But! for conduction, the rate of extraction of heat is

$$\frac{dQ}{dt} = -\frac{kA}{L}(T - T_s)$$

- $kA$ indicates a temperature decrease w.r.t. time

Thus:

$$\frac{dT}{dt} = \frac{kA}{mcL}(T - T_s) \quad \text{--- Eqn. 1}$$

$$\int \frac{1}{T - T_s} \, dT = \int \frac{kA}{mcL} \, dt$$

$$\ln(T - T_s) + C = -\frac{kA}{mcL}t$$

$$\ln(T - T_s) = \ln(T_c - T_s) - \frac{kA}{mcL}t$$

This equation gives the temperature $T$ at any time $t$.

At $t = 0$, $T = T_c$, so, inserting into Eqn. 1, we get an expression for the initial rate of cooling:

$$\frac{dT}{dt} = -\frac{kA}{mcL}(T_c - T_s)$$
Newton’s law of cooling

This is an empirical law which relates the rate of temperature change to the temperature of the body compared to the surroundings. It takes into account conduction, convection and radiation (mainly convection) and is an empirical law.

\[
\frac{dT}{dt} = -K(T - T_s)
\]

This formula is almost the same as that worked out previously for cooling by conduction only. Here, the factor \( K \) embodies conduction, convection and radiation effects.

TRANSIENT (UNSTEADY-STATE) HEAT TRANSFER

Boiling water 100°C

Solid food material
\( T_{s,\text{initial}} = 35°C \)

Change in temperature??

\( T_s = f(t,r) \)
Transient (Unsteady-State) Heat Transfer

- Importance of internal and external resistance to heat transfer
- Relative importance of conductive and convective heat transfer
- Biot number, \( N_{\text{Bi}} = \frac{hD}{k} \)

\[
N_{\text{Bi}} = \frac{D}{k} \cdot \frac{1}{h}
\]

or \( N_{\text{Bi}} = \frac{\text{Internal resistance to heat transfer}}{\text{External resistance to heat transfer}} \)

Transitory (Unsteady-State) Heat Transfer

- Negligible internal resistance
  \( \ldots \rightarrow N_{\text{Bi}} < 0.1 \)

\[
q = \rho V C_p \frac{dT}{dt} = h A (T_a - T)
\]

\[
\int \frac{dT}{T_a - T} = \int \frac{\frac{h A}{\rho C_p V} \, dt}{T_i - T}
\]

\[
\ln(T_a - T) = \frac{h A t}{\rho C_p V}
\]

\[
T_a - T = e^{-\left(\frac{h A}{\rho C_p V}\right) t}
\]

\[
\frac{T_a - T}{T_a - T_0} = e^{\left(\frac{h A}{\rho C_p V}\right) t}
\]
**Finite Surface and Internal Resistance To Heat Transfer**

\[ 0.1 < N_{Bi} < 40 \quad \Rightarrow \quad m = 1/N_{Bi} \]

**Negligible Surface Resistance To Heat Transfer**

\[ N_{Bi} > 40 \quad \Rightarrow \quad m = 1/N_{Bi} = 0 \]

Infinite Slab, infinite cylinder and sphere
Use Gurnie-Lurie Chart and/or Heisler Chart
\[ \Rightarrow \text{temperature-time (T-t) chart} \]

Dimensionless number : Fourier number \( N_{Fo} \)

\[
N_{Fo} = \frac{kt}{\rho C_p D^2} = \frac{\alpha t}{D^2}
\]

- \( D \) = characteristic dimension
- \( D_{sphere} \) = radius
- \( D_{inf cylinder} \) = radius
- \( D_{inf slab} \) = half thickness

**The physical meaning of Fourier Number :**

\[
N_{Fo} = \frac{\alpha t}{D^2} = \frac{k \left( \frac{1}{D} \right) D^2}{\rho C_p D^3 \left( \frac{1}{t} \right)}
\]

\[
N_{Fo} = \frac{\text{Rate of heat conduction across } D \text{ in volume } D^3}{\text{Rate of heat storage in volume } D^3}
\]

Large value of \( N_{Fo} \) indicates deeper penetration of heat into solid in a given period of time.
Prosedur pengunaan diagram T-t

1. Untuk silinder tak berbatas

Suhu pusat (sumbu) silinder setelah pemanasan selama t?

a. hitung $N_{Fo}$, gunakan R sebagai D
b. hitung $N_{Bi}$, gunakan R sebagai D  \[ \Rightarrow \text{hitung } 1/N_{Bi} = m = k/hD \]
c. gunakan diagram untuk silinder tak berbatas, dari $N_{Fo}$ dan $N_{Bi}$ cari ratio $T$

Diagram T-t : hubungan antara suhu di sumbu silinder dan $N_{Fo}$
2. Untuk lempeng tak berbatas ketebalan, \( X = 2D \)
lebar = \( \infty \); panjang = \( \infty \)

Suhu ditengah (midplane) lempeng tak berbatas setelah pemanasan selama \( t \) ??

a. hitung \( N_{Fo} \), gunakan \((1/2)X\) sebagai \( D \)
b. hitung \( N_{Bi} \), gunakan \((1/2)X\) sebagai \( D \) -> hitung \( 1/N_{Bi} \)
c. gunakan diagram untuk lempeng tak berbatas,
dari \( N_{Fo} \) dan \( N_{Bi} \) cari ratio \( T \)

TRANSIENT (UNSTEADY-STATE) HEAT TRANSFER

Diagram T-t : hubungan suhu di "midplane" lempeng tak berbatas dan \( N_{Fo} \)
Diagram T-t : hubungan antara suhu di pusat bola dan N\textsubscript{Fo}

TRANSIENT (UNSTABLE) HEAT TRANSFER

1. Menentukan suhu setelah pemanasan/pendinginan
   - cari nilai \( N\text{Fo} = \frac{\alpha}{\delta^2} \)
   - cari nilai \( N\text{bi} \) dan \( m = 1/N\text{bi} \)
   - tentukan posisi dimana suhu ingin diketahui, \( n = x/\delta \)
   - cari ratio suhu

2. Menentukan waktu pemanasan/pendinginan untuk mencapai suhu \( t_{tt} \)
   - cari rasio suhu, pada posisi \( t_{tt} \) yang diketahui, \( n = r/R \)
   - cari nilai \( N\text{bi} \) dan \( m = 1/N\text{bi} \)
   - cari \( N\text{Fo} = \frac{\alpha}{\delta^2} \); dan hitung \( t \)
TRANSIENT (UNSTEADY-STATE) HEAT TRANSFER

Diagram Gurnie-Lurie untuk SILINDER:

1. Menentukan suhu setelah pemanasan/pendinginan
   - cari nilai $N_{Fo} = \alpha t/R^2$
   - cari nilai $N_{bi}$ dan $m=1/N_{bi}$
   - tentukan posisi dimana suhu ingin diketahui, $n = r/R$
   - cari ratio suhu

2. Menentukan waktu pemanasan/pendinginan untuk mencapai suhu $ttt$
   - cari rasio suhu, pada posisi $ttt$ yang diketahui, $n = r/R$
   - cari nilai $N_{Fo}$ dan $m=1/N_{bi}$
   - cari $N_{Fo} = \alpha t/R^2$; dan hitung $t$

Diagram Gurnie-Lurie untuk BOLA:

1. Menentukan suhu setelah pemanasan/pendinginan
   - cari nilai $N_{Fo} = \alpha t/R^2$
   - cari nilai $N_{bi}$ dan $m=1/N_{bi}$
   - tentukan posisi dimana suhu ingin diketahui, $n = r/R$
   - cari ratio suhu

2. Menentukan waktu pemanasan/pendinginan untuk mencapai suhu $ttt$
   - cari rasio suhu, pada posisi $ttt$ yang diketahui, $n = r/R$
   - cari nilai $N_{Fo}$ dan $m=1/N_{bi}$
   - cari $N_{Fo} = \alpha t/R^2$; dan hitung $t$

Fig. 7.15. Heizer chart for the center temperature of a slab. (Adapted from Hou, S. T. 1963. Engineering Heat Transfer. Van Nostrand Reinhold, New York.)
TRANSIENT (UNSTEADY-STATE) HEAT TRANSFER

Finite object \( \rightarrow \) finite slab \((\text{bentuk bata, panjang}=l, \text{lebar}=w, \text{tinggi}=h)\)

\[
\frac{T_a - T}{T_a - T_i} = \left(\frac{T_a - T_i}{T_a - T_f}\right)_{\text{Inf. slab}} \times \left(\frac{T_a - T}{T_a - T_i}\right)_{\text{Inf. slab}} \times \left(\frac{T_a - T_i}{T_a - T_f}\right)_{\text{Inf. slab}}
\]

**Fig. 7.16.** Nusselt chart for the surface temperature of a slab. (Adapted from Hsu, S. T. 1963. Engineering Heat Transfer. Van Nostrand Reinhold, New York.)
TRANSIENT (UNSTEADY-STATE) HEAT TRANSFER

Finite object ……> finite slab (bentuk kaleng, jari-jari=R, tinggi=h)

\[
\frac{T_a - T}{T_a - T_i} = \frac{T_a - T}{T_a - T_i} \times \frac{T_a - T}{T_a - T_i} \\
\]

- for finite cylinder, radius R, thickness=h
- for infinite cylinder, radius R

TRANSIENT (UNSTEADY-STATE) HEAT TRANSFER

Penentuan posisi pada benda berbatas

Lokasi: tengah tutup kaleng
- ditengah silinder: n=0
- dipermukaan lempeng: n=1

Lokasi x
- n silinder = r/R = 1/2
- n lempeng = x/δ = 1/2

\[
X = \frac{1}{2}\delta \\
\]
CONTOH SOAL

Apel didinginkan dari suhu 20°C menjadi 8°C, dengan menggunakan air dingin mengalir (5°C). Aliran air dingin ini memberikan koef. Heat Transfer konvensi sebesar 10 M/m².K. Asumsikan apel sebagai bola dengan diameter 8 cm. Nilai k apel = 0.4 W/m/K, Cp apel= 3.8 kJ/kg.K dan densitasnya=960 kg/m³. Untuk pusat geometri apel mencapai suhu 8°C, berapa lama harus dilakukan pendinginan?

Jawab :
1. Cek NBi ; apakah nilainya <0.1?  
   0.1<NBi<40?  
   atau NBi >40??  
   NBi= (hR/k)=1 ...........> 0.1<NBi<40 : gunakan diagram T-t (m=1/NBi=1)
2. Hitung rasio suhu yang dikehendaki :  
   (Ta-T)/(Ta-Ti)=(5-8)/(5-20)=0.2
3. Posisi? Di pusat geometri ......> n=0
4. Cari nilai NFo, dan tentukan t

\[ N_{Fo} = \frac{\alpha t}{R^2} = 0.78 \]
\[ t = \frac{0.78R^2}{\alpha} \]
\[ t = \frac{0.78R^2}{[k/(\rhoC_p)]} \]
\[ t = \frac{0.78(0.04)^2/[0.4/(960)(3800)]}{ } \]
\[ t = 11,381 \text{ s} \]
\[ t = 3.16 \text{ h} \]