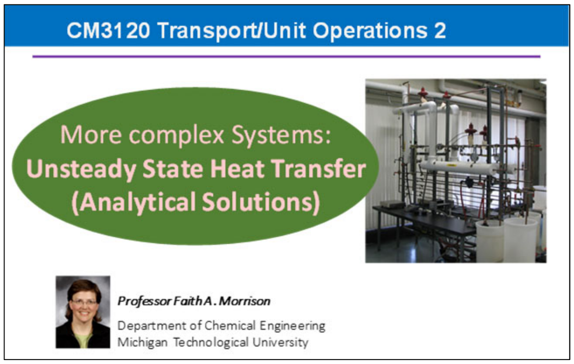
Last time,
Unsteady State Heat Transfer



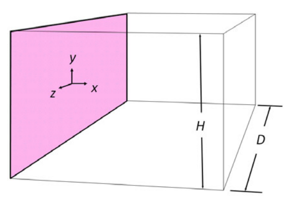
Exploring the "lay of the land"

 1

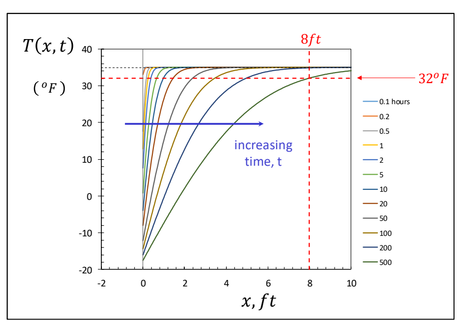
Solution Summary:

Example:
When will my pipes freeze?

The temperature has been 35°F for a while now, sufficient to chill the ground to this temperature for many tens of feet below the surface. Suddenly the temperature drops to -20°F. How long will it take for freezing temperatures (32°F) to reach my pipes, which are 8 *ft* under ground?



Answer:
$$t = 509\ hours \approx 21\ days$$



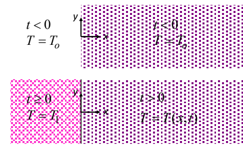
 2

Dimensional Analysis, Unsteady State Convection

Non-dimensionalize (eqns, BCs)

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial x^2}\right)$$

$$q_x = -k\frac{\partial T}{\partial x} = hA(T_1 - T)$$



non-dimensional variables:

position: $x^* \equiv \frac{x}{D}$

temperature: $Y \equiv \frac{(T_1 - T)}{(T_1 - T_0)}$

time: $t^* \equiv \frac{\alpha t}{D^2}$

Note: $D = D\_char$ and this length scale is not always "diameter"

This dimensionless time is called Fourier number Fo.

$$\text{Fo} - \text{Fourier Number} = \frac{\alpha t}{D^2}$$

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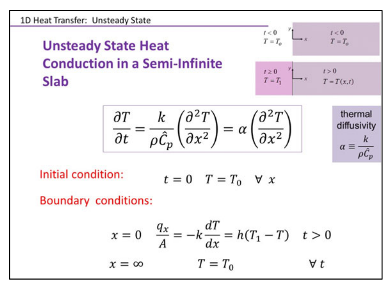
In dimensionless form, we see that this problem reduces to

$$Y = Y\left(\frac{x}{D}, \text{Fo}, \text{Bi}\right)$$


1D Heat Transfer: Unsteady State

Unsteady State Heat Conduction in a Semi-Infinite Slab

$$\frac{\partial T}{\partial t} = \frac{k}{\rho\hat{C}_p}\left(\frac{\partial^2 T}{\partial x^2}\right) = \alpha\left(\frac{\partial^2 T}{\partial x^2}\right)$$

thermal diffusivity $\alpha \equiv \frac{k}{\rho\hat{C}_p}$

Initial condition: $t = 0 \quad T = T_0 \quad \forall\, x$

Boundary conditions:

$x = 0 \quad \frac{q_x}{A} = -k\frac{dT}{dx} = h(T_1 - T) \quad t > 0$

$x = \infty \quad T = T_0 \quad \forall\, t$

Dimensionless quantities:

$Y = \frac{(T_1 - T)}{(T_1 - T_0)}$ — **Y** (dimensionless temperature interval)

$t^* = \text{Fo} = \frac{\alpha t}{D^2}$ — **Fourier number** (dimensionless time based on thermal diffusion)

$x^* = \frac{x}{D}$

$\text{Bi} = \frac{hD}{k}$ — **Biot number** (pronounced BEE-OH) Ratio of heat transfer resistance at the boundary to resistance in the solid. This is a *transport* issue.

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$\text{Bi} - \text{Biot Number} = \frac{hD}{k}$

$$\text{Bi} = \frac{D_{char}/k}{1/h}$$

Quantifies the tradeoffs between the rate of internal heat flux (by conduction, k) and the rate of heat delivery to the boundary (by convection, h)

At high Bi, the surface temperature equals the bulk temperature; heat transfer is limited by conduction in the body.

High Bi:
low k,
high h

At moderate Bi, heat transfer is affected by both conduction in the body and the rate of heat transfer to the surface.

Moderate Bi:
nether process dominates

At low Bi, the temperature is uniform in a finite body; heat transfer is limited by rate of heat transfer to the surface (h).

Low Bi:
high k,
low h

5

$\text{Bi} - \text{Biot Number} = \frac{hD}{k}$

$$\text{Bi} = \frac{D_{char}/k}{1/h}$$

Quantifies the tradeoffs between the rate of internal heat flux (by conduction, k) and the rate of heat delivery to the boundary (by convection, h)

At high Bi, the surface temperature equals the bulk temperature; heat tra... th...

High Bi:
low k,

When the temperature is uniform in the body, we can do a macroscopic energy balance to solve many problems of interest. This is called a "**lumped parameter analysis**."

At... aff... bo... the surface.

dominates

$$T = T(t)$$

At low Bi, the temperature is uniform in a finite body; heat transfer is limited by rate of heat transfer to the surface (h).

Low Bi:
high k,
low h

6

Bi – Biot Number $= \frac{hD}{k}$

Quantifies the tradeoffs between the rate of internal heat flux (by conduction, k) and the rate of heat delivery to the boundary (by convection, h)

$$\mathrm{Bi} = \frac{D_{char}/k}{1/h}$$

$T = T(x, y, z, t)$, **easy BC**

At high Bi, <u>the surface temperature equals the bulk temperature</u>; heat transfer is limited by conduction in the body.

High Bi: low k, high h

At moderate Bi, heat transfer is affected by ... body and t... the surface...

Moderate Bi:

At low Bi, t... <u>uniform in</u> ... transfer is limited by rate of heat transfer to the surface (h).

... high k, low h

When the wall temperature and the bulk temperature are equal, the microscopic energy balance is easier to carry out (temperature boundary conditions).

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Bi – Biot Number $= \frac{hD}{k}$

Quantifies the tradeoffs between the rate of internal heat flux (by conduction, k) and the rate of heat delivery to the boundary (by convection, h)

$$\mathrm{Bi} = \frac{D_{char}/k}{1/h}$$

When both processes affect the outcomes, the full solution may be necessary. For uniform starting temperatures, the solutions are published.

... the body.

... high h

$T = T(x, y, z, t)$ **hard BC**

At moderate Bi, heat transfer is affected by <u>both</u> conduction in the body and the rate of heat transfer to the surface.

Moderate Bi: nether process dominates

At low Bi, the temperature is <u>uniform in a finite body</u>; heat transfer is limited by rate of heat transfer to the surface (h).

Low Bi: high k, low h

 8

1. Lumped parameter analysis

(negligible internal resistance $1/k$)

$$\mathrm{Bi}_{LP} < 0.1$$

Bi – Biot Number $= \frac{hD}{k}$

Quantifies the tradeoffs between the rate of internal heat flux (by conduction, k) and the rate of heat delivery to the boundary (by convection, h)

At high Bi, the surface temperature equals the bulk temperature; heat

High Bi:

When the temperature is uniform in the body, we can do a macroscopic energy balance to solve many problems of interest. This is called a "lumped parameter analysis."

the surface.

dominates

At low Bi, the temperature is uniform in a finite body; heat transfer is limited by rate of heat transfer to the surface (h).

Low Bi: high k, low h

Low Bi:
high k,
low h

At low Bi, the temperature is uniform in a finite body; heat transfer is limited by rate of heat transfer to the surface (h).

$$\mathrm{Bi}_{LP} = \frac{hV_{sys}}{kA_{sys}}$$

$$D_{char} \equiv \frac{\text{volume}}{\text{area}} = \frac{V_{sys}}{A_{sys}}$$

This is always the D_{char} we use for the lumped parameter analysis. We use different D_{char} in other cases, however.

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This topic is part of a more general subject:

CM3120 Transport/Unit Operations 2

Unsteady Macroscopic Energy Balance

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Michigan Technological University

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Unsteady State Heat Transfer: Low Biot Number

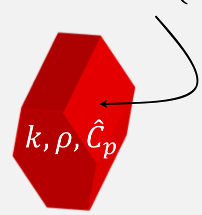
$$\mathrm{Bi}_{LP} = \frac{hV_{sys}}{kA_{sys}}$$

Example: Quench cooling of a manufactured part.

If a piece of steel with $T = T_0$ is dropped into a large, well stirred reservoir of fluid at bulk temperature T_∞, what is the temperature of the steel as a function of time?

- k = large, which means that there is no internal resistance to heat transfer in the part
- Therefore, we are NOT calculating a temperature profile (internal T is uniform)
- **⇒ Use Unsteady, Macroscopic Energy Balance**

$T = T(t)$



Fluid temperature= T_∞

Unsteady State Heat Transfer: Low Biot Number

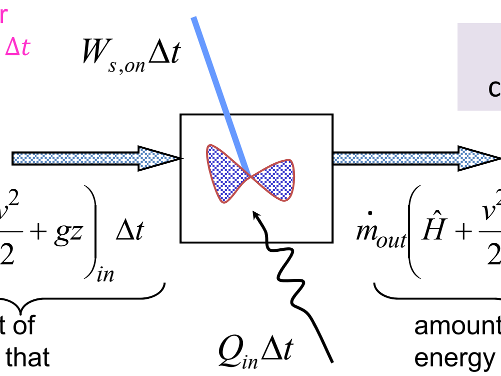
Unsteady Macroscopic Energy Balance

see Felder and Rousseau or Himmelblau

balance over time interval Δt

Macroscopic control volume

$W_{s,on}\Delta t$



$$\underbrace{\dot{m}_{in}\left(\hat{H} + \frac{v^2}{2} + gz\right)_{in}\Delta t}_{\text{amount of energy that enters with the flow between } t \text{ and } t+\Delta t}$$

$Q_{in}\Delta t$

$$\underbrace{\dot{m}_{out}\left(\hat{H} + \frac{v^2}{2} + gz\right)_{out}\Delta t}_{\text{amount of energy that exits with the flow between } t \text{ and } t+\Delta t}$$

Unsteady State Heat Transfer: Low Biot Number

Unsteady Macroscopic Energy Balance

$$accumulation = input - output$$

$$\frac{d}{dt}\left(U_{sys} + E_{k,sys} + E_{p,sys}\right) = -\Delta H - \Delta E_k - \Delta E_p + Q_{in} + W_{s,on}$$

Background:
pages.mtu.edu/~fmorriso/cm310/IFMWeb
AppendixDMicroEBalanceMorrison.pdf

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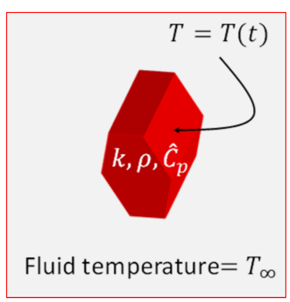
Unsteady State Heat Transfer: Low Biot Number

Unsteady Macroscopic Energy Balance

$$accumulation = input - output$$

$$\frac{d}{dt}\left(U_{sys} + E_{k,sys} + E_{p,sys}\right) = -\Delta H - \Delta E_k - \Delta E_p + Q_{in} + W_{s,on}$$

How do we apply this balance to our current problem?



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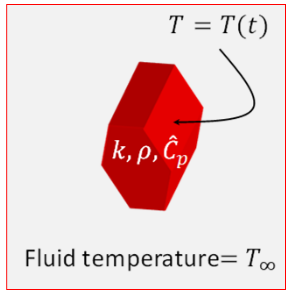
Unsteady State Heat Transfer: Low Biot Number

Unsteady Macroscopic Energy Balance

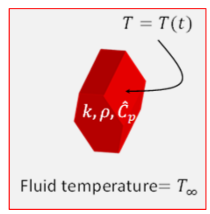
$$accumulation = input - output$$

$$\frac{d}{dt}\left(U_{sys} + E_{k,sys} + E_{p,sys}\right) = -\Delta H - \Delta E_k - \Delta E_p + Q_{in} + W_{s,on}$$



You try.

Unsteady State Heat Transfer: Low Biot Number



Unsteady Macroscopic Energy Balance

$$accumulation = input - output$$

$$\frac{d}{dt}\left(U_{sys} + \cancel{E_{k,sys}} + \cancel{E_{p,sys}}\right) = -\cancel{\Delta H} - \cancel{\Delta E_k} - \cancel{\Delta E_p} + Q_{in} + \cancel{W_{s,on}}$$

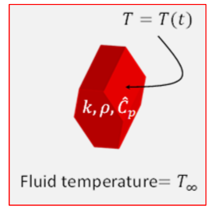
negligible　　no flow　　no shafts

For negligible changes in E_p and E_k, no flow, no phase change, no chemical rxn, and no shafts:

$$\boxed{\begin{gathered}\frac{dU_{sys}}{dt} = Q_{in} \\ \rho V_{sys}\hat{C}_v\frac{dT_{sys}}{dt} = Q_{in}\end{gathered}}$$

$\hat{C}_v \approx \hat{C}_p$ for liquids, solids

Unsteady State Heat Transfer: Low Biot Number



Unsteady Macroscopic Energy Balance

How do we quantify the heat in Q_{in}?

$$\frac{d}{dt}\left(U_{sys} + \cancel{E_{k,sys}} + \cancel{E_{p,sys}}\right) = \cancel{-\Delta H} - \cancel{\Delta E_k} - \cancel{\Delta E_p} + Q_{in} + \cancel{W_{s,on}}$$

negligible no flow no shafts

For negligible changes in E_p and E_k, no flow, no phase change, no chemical rxn, and no shafts:

$$\frac{dU_{sys}}{dt} = Q_{in}$$

$$\rho V_{sys} \hat{C}_v \frac{dT_{sys}}{dt} = Q_{in}$$

$\hat{C}_v \approx \hat{C}_p$ for liquids, solids

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Unsteady Macroscopic Energy Balance

accumulation = input − output

Q_{in} = Heat ***in***to the chosen macroscopic control volume

$$\frac{d}{dt}\left(U_{sys} + E_{k,sys} + E_{p,sys}\right) = -\Delta H - \Delta E_k - \Delta E_p + Q_{in} + W_{s,on}$$

$Q_{in} = \sum_i q_{in,i}$ comes from a variety of sources:

- Thermal conduction: $q_{in} = -kA\frac{dT}{dx}$
- Convection heat xfer: $|q_{in}| = |hA(T_b - T)|$
- Radiation: $q_{in} = \varepsilon\sigma A\left(T^4_{surroundings} - T^4_{surface}\right)$
- Electric current: $q_{in} = I^2 R_{elec} L$
- Chemical Reaction: $q_{in} = S_{rxn} V_{sys}$

$S[=]\frac{\text{energy}}{\text{time volume}}$

pages.mtu.edu/~fmorriso/cm310/IFMWebAppendixDMicroEBalanceMorrison.pdf

Incropera and DeWitt, 6th edition p18

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Unsteady Macroscopic Energy Balance

accumulation = input − output

Q_{in} = Heat ***in***to the chosen macroscopic control volume

$$\frac{d}{dt}\left(U_{sys}+E_{k,sys}+E_{p,sys}\right)=-\Delta H-\Delta E_k-\Delta E_p+Q_{in}+W_{s,on}$$

$Q_{in}=\sum_i q_{in,i}$ comes from a variety of sources:

Signs must match transfer from outside (bulk fluid) to inside (metal)

- Thermal conduction: $q_{in}=-kA\frac{dT}{dx}$
- Convection heat xfer: $|q_{in}|=|hA(T_b-T)|$
- Radiation: $q_{in}=\varepsilon\sigma A\left(T^4_{surroundings}-T^4_{surface}\right)$
- Electric current: $q_{in}=I^2R_{elec}L$
- Chemical Reaction: $q_{in}=S_{rxn}V_{sys}$

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Incropera and DeWitt, 6th edition p18

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Unsteady Macroscopic Energy Balance

$$\frac{d}{dt}\left(U_{sys}+E_{k,sys}+E_{p,sys}\right)=-\Delta H-\Delta E_k-\Delta E_p+Q_{in}+W_{s,on}$$

$Q_{in}=\sum_i q_{in,i}$ comes from a variety of sources:

- **Thermal conduction: $q_{in}=-kA\frac{dT}{dx}$**

  e.g. device held by bracket; a solid phase that extends through boundaries of control volume

- **Convection heat xfer: $|q_{in}|=|hA(T_b-T)|$**

  e.g. device dropped in stirred liquid; forced air stream flows past, natural convection occurs outside system; phase change at boundary

- **Radiation: $q_{in}=\varepsilon\sigma A\left(T^4_{surroundings}-T^4_{surface}\right)$**

  e.g. device at high temp. exposed to a gas/vacuum; hot enough to produce nat. conv.=possibly hot enough for radiation

S-B constant: $\sigma=5.676\times10^{-8}\frac{W}{m^2K^4}$

- **Electric current: $q_{in}=I^2R_{elec}L$**

  e.g. if electric current is flowing within the device/control volume/ system

- **Chemical Reaction: $q_{in}=S_{rxn}V_{sys}$**

  e.g. if a homogeneous reaction is taking place throughout the device/ control volume/system

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Unsteady Macroscopic Energy Balance

accumulation = input − output

Q_{in} = Heat ***in***to the chosen macroscopic control volume

$$\frac{d}{dt}\left(U_{sys}+E_{k,sys}+E_{p,sys}\right)=-\Delta H-\Delta E_k-\Delta E_p+Q_{in}+W_{s,on}$$

$Q_{in}=\sum_i q_{in,i}$ comes from a variety of sources:

- X • Thermal conduction: $q_{in}=-kA\frac{dT}{dx}$
- ✓ • Convection heat xfer: $|q_{in}|=|hA(T_b-T)|$
- X • Radiation: $q_{in}=\varepsilon\sigma A\left(T_{surroundings}^4-T_{surface}^4\right)$
- X • Electric current: $q_{in}=I^2R_{elec}L$
- X • Chemical Reaction: $q_{in}=S_{rxn}V_{sys}$

$S[=]\frac{\text{energy}}{\text{time volume}}$

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Incopera and DeWitt, 6th edition p18

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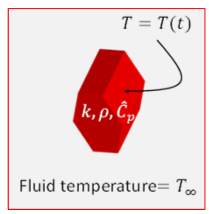
Unsteady State Heat Transfer: Low Biot Number



Unsteady Macroscopic Energy Balance Applied to cooling steel part:

$$\underbrace{\rho V_{sys}\hat{C}_p\frac{dT_{sys}}{dt}}=\mathrm{Q}_{in}$$

The temperature changes in the part are due to the heat loss

The heat loss depends on the heat-transfer coefficient from the part to the environment

$$\boxed{\mathrm{Q}_{in}=Ah(T_\infty-T)}$$

$\hat{C}_v\approx\hat{C}_p$ for liquids, solids

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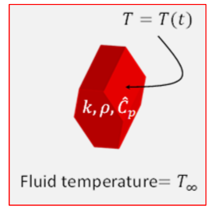
Unsteady State Heat Transfer: Low Biot Number



Unsteady Macroscopic Energy Balance Applied to cooling steel part:

$$\underbrace{\rho V_{sys} \hat{C}_p \frac{dT_{sys}}{dt}}_{\text{The temperature changes in the part are due to the heat loss}} = Q_{in}$$

The heat loss depends on the heat-transfer coefficient from the part to the environment

$$\boxed{Q_{in} = Ah(T_\infty - T)}$$

You solve.

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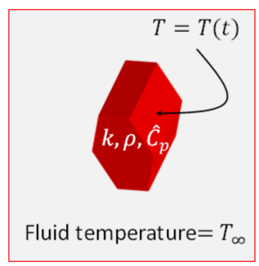
Unsteady State Heat Transfer: Low Biot Number



Unsteady Macroscopic Energy Balance Applied to cooling steel part:

$$\boxed{\frac{(T_\infty - T)}{(T_\infty - T_0)} = e^{-\left(\frac{hA}{\rho \hat{C}_p V}\right) t}}$$

$V_{sys} = V$

$$\boxed{\ln\left(\frac{(T_\infty - T)}{(T_\infty - T_0)}\right) = -\left(\frac{hA}{\rho \hat{C}_p V}\right) t}$$

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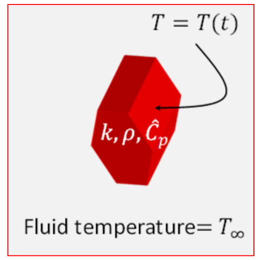
Unsteady State Heat Transfer: Low Biot Number

Unsteady Macroscopic Energy Balance Applied to cooling steel part:



$$\frac{(T_\infty - T)}{(T_\infty - T_0)} = e^{-\left(\frac{hA}{\rho \hat{C}_p V}\right)t}$$

$$V_{sys} = V$$

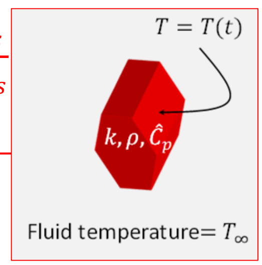
$$\ln\left(\frac{(T_\infty - T)}{(T_\infty - T_0)}\right) = -\left(\frac{hA}{\rho \hat{C}_p V}\right)t$$

In dimensionless form?

Unsteady State Heat Transfer: Low Biot Number

$$\mathrm{Bi}_{LP} = \frac{hV_{sys}}{kA_{sys}}$$

Unsteady Macroscopic Energy Balance Applied to cooling steel part:



$$\frac{(T_\infty - T)}{(T_\infty - T_0)} = e^{-\left(\frac{hA}{\rho \hat{C}_p V}\right)t}$$

$$\frac{hAt}{\rho \hat{C}_p V} = \left(\frac{h}{k}\right)\left(\frac{k}{\rho \hat{C}_p}\right)\left(\frac{A}{V}\right)t = \left(\frac{\mathrm{Bi}}{D_{char}}\right)\alpha\left(\frac{t}{D_{char}}\right) = \mathrm{Bi\ Fo}$$

LP good for: $\mathrm{Bi}_{LP} < 0.1$

$D_{char} \equiv \frac{\text{volume}}{\text{area}} = \frac{V}{A}$

thermal diffusivity $\alpha \equiv \frac{k}{\rho \hat{C}_p}$

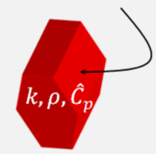
Bi – Biot Number $= \frac{hD_{char}}{k}$

Fo – Fourier Number $= \frac{\alpha t}{D_{char}^2}$

Unsteady State Heat Transfer: Low Biot Number

$$\text{Bi}_{LP} = \frac{hV_{sys}}{kA_{sys}}$$

Unsteady Macroscopic Energy Balance Applied to cooling steel part:



$$\boxed{Y = \frac{(T_\infty - T)}{(T_\infty - T_0)} = e^{-\text{Bi Fo}}}$$

Lumped parameter analysis

WRF p279

https://en.wikipedia.org/wiki/Lumped_element_model

Lumped parameter analysis:

LP good for: $\text{Bi}_{LP} < 0.1$

$$\text{Bi} - \text{Biot Number} = \frac{hD_{\text{char}}}{k} = \frac{hV}{kA}$$

$$\text{Fo} - \text{Fourier Number} = \frac{\alpha t}{D_{\text{char}}^2}$$

$$D_{char} \equiv \frac{\text{volume}}{\text{surf. area}} = \frac{V}{A}$$

thermal diffusivity

$$\alpha \equiv \frac{k}{\rho \hat{C}_p}$$

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Unsteady State Heat Transfer

Summary

$$\text{Bi}_{LP} = \frac{hV_{sys}}{kA_{sys}}$$

LP good for: $\text{Bi}_{LP} < 0.1$

Quantifies the tradeoffs between the rate of internal heat flux (by conduction, k) and the rate of heat delivery to the boundary (by convection, h)

At high Bi, the surface temperature equals the bulk temperature; heat tran... the...

High Bi:

At m... affe... bod... the surface.

dominates

When the temperature is uniform in the body, we can do a macroscopic energy balance to solve many problems of interest. This is called a "lumped parameter analysis."

At low Bi, the temperature is uniform in a finite body; heat transfer is limited by rate of heat transfer to the surface (h).

Low Bi: high k, low h

Low Bi: no internal temperature variation ⇒ Lumped parameter analysis (macroscopic energy balance, unsteady); $\text{Bi}_{LP} = hV/kA < 0.1$

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2. Negligible Surface Resistance, $\frac{1}{h}$

$\text{Bi} - \text{Biot Number} = \frac{hD}{k}$

Quantifies the tradeoffs between the rate of internal heat flux (by conduction, k) and the rate of heat delivery to the boundary (by convection, h)

At high Bi, the surface temperature equals the bulk temperature; heat transfer is limited by conduction in the body.

High Bi: low k, high h

At moderate Bi, heat transfer is affected by ... body and t... the surface

Moderate Bi:

At low Bi, t... uniform in ... transfer is limited by rate of heat transfer to the surface (h).

high k, low h

When the wall temperature and the bulk temperature are equal, the microscopic energy balance is easier to carry out (temperature boundary conditions).

High Bi:
low k,
high h

At high Bi, the surface temperature equals the bulk temperature; heat transfer is limited by conduction in the body.

Negligible Surface Resistance, $\frac{1}{h}$

$\text{Bi} - \text{Biot Number} = \frac{hD}{k}$

Quantifies the tradeoffs between the rate of internal heat flux (by conduction, k) and the rate of heat delivery to the boundary (by convection, h)

At high Bi, the surface temperature equals the bulk temperature; heat transfer is limited by conduction in the body.

High Bi: low k, high h

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high k, low h

When the wall temperature and the bulk temperature are equal, the microscopic energy balance is easier to carry out (temperature boundary conditions).

High Bi:
low k,
high h

At high Bi, the surface temperature equals the bulk temperature; heat transfer is limited by conduction in the body.

$$\lim_{h\to\infty} |T_{bulk} - T_{wall}| = 0$$

$$\Rightarrow T_{wall} = T_{bulk}$$

We have done many examples with constant temperature boundary conditions.

Unsteady State Heat Transfer

Summary

High Bi: dominated by internal temperature variation ⇒ solve with temperature boundary conditions; $\mathrm{Bi} = hD_{char}/k$ **(D_{char} varies with the problem)**

Bi – Biot Number $= \frac{hD}{k}$

Quantifies the tradeoffs between the rate of internal heat flux (by conduction, k) and the rate of heat delivery to the boundary (by convection, h)

At high Bi, the surface temperature equals the bulk temperature; heat transfer is limited by conduction in the body.

High Bi: low k, high h

When the wall temperature and the bulk temperature are equal, the microscopic energy balance is easier to carry out (temperature boundary conditions).

transfer is limited by rate of heat transfer to the surface (h).

high k, low h

Low Bi: no internal temperature variation ⇒ Lumped parameter analysis (macroscopic energy balance, unsteady); $\mathrm{Bi}_{LP} = hV/kA < 0.1$

LP good for: $\mathrm{Bi}_{LP} < 0.1$

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3. No Mechanism Dominates

Moderate Bi: nether process dominates

Bi – Biot Number $= \frac{hD}{k}$

Quantifies the tradeoffs between the rate of internal heat flux (by conduction, k) and the rate of heat delivery to the boundary (by convection, h)

When both processes affect the outcomes, the full solution may be necessary; for uniform starting temperatures there are charts.

At moderate Bi, heat transfer is affected by both conduction in the body and the rate of heat transfer to the surface.

Moderate Bi: nether process dominates

At low Bi, the temperature is uniform in a finite body; heat transfer is limited by rate of heat transfer to the surface (h).

Low Bi: high k, low h

At moderate Bi, heat transfer is affected by both conduction in the body and the rate of heat transfer to the surface.

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Moderate Bi:
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This is the most complicated set of cases.

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