
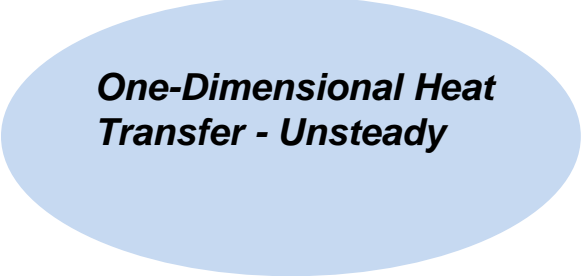
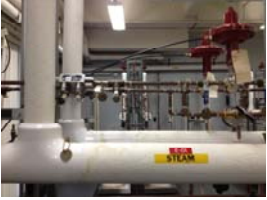


**CM3110  
Transport I  
Part II: Heat Transfer**









**Professor Faith Morrison**

Department of Chemical Engineering  
Michigan Technological University

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CM3110  
Transport I  
Part II: Heat Transfer

**One-Dimensional Heat Transfer**  
(part 2: cylindrical shell)

Professor Faith Morrison  
Department of Chemical Engineering  
Michigan Technological University

## SUMMARY

Steady State Heat Transfer

Example 1: Heat flux in a rectangular solid – Temperature BC

Example 2: Heat flux in a rectangular solid – Newton’s law of cooling

Example 3: Heat flux in a cylindrical shell – Temperature BC

Example 4: Heat flux in a cylindrical shell – Newton’s law of cooling



Example 5: Heat conduction with generation

Example 6: Wall heating of laminar flow

**Conclusion:** When we can simplify geometry, assume steady state, assume symmetry, the solutions are easily obtained

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CM3110  
Transport I  
Part II: Heat Transfer

**One-Dimensional Heat Transfer**  
(part 2: cylindrical shell)

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## SUMMARY

### Steady State Heat Transfer

Example 1: Heat flux in a rectangular solid – Temperature BC

Example 2: Heat flux in a rectangular solid – Newton's law of cooling

Example 3: Heat flux in a cylindrical shell – Temperature BC

Example 4: Heat flux in a cylindrical shell – Newton's law of cooling

Example 5: Heat conduction with generation

Example 6: Wall heating of laminar flow

**Conclusion:** When we can simplify geometry, assume steady state, assume symmetry, the solutions are easily obtained

What about non-steady-state problems (quite common in heat transfer)?

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### 1D Heat Transfer: Unsteady State

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**Example 1: Unsteady Heat Conduction in a Semi-infinite solid**

A very long, very wide, very tall slab is initially at a temperature  $T_o$ . At time  $t = 0$ , the left face of the slab is exposed to an environment at temperature  $T_1$ . What is the time-dependent temperature profile in the slab? The slab is a homogeneous material of thermal conductivity,  $k$ , density,  $\rho$ , and heat capacity,  $C_p$ .

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1D Heat Transfer: Unsteady State

**Example 1: Unsteady Heat Conduction in a Semi-infinite solid**

A very long, very wide, very tall slab is initially at a temperature  $T_0$ . At time  $t = 0$ , the left face of the slab is **exposed to an environment** at temperature  $T_1$ . What is the time-dependent temperature profile in the slab? The slab is a homogeneous material of thermal conductivity,  $k$ , density,  $\rho$ , and heat capacity,  $C_p$ .

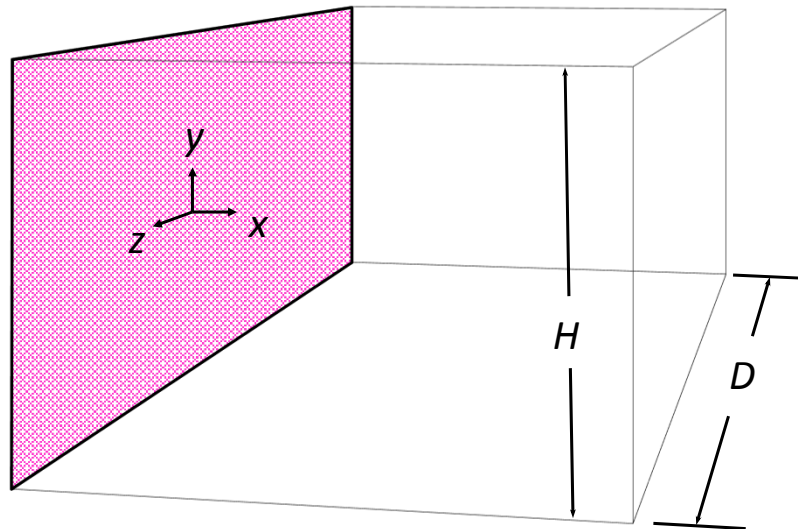
**This is code for:**

“Newton’s law of cooling boundary conditions:”  
 $|\text{flux}| = h|T_{\text{bulk}} - T_{\text{wall}}|$

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**Unsteady State Heat Transfer**

Example: Unsteady Heat Conduction in a Semi-infinite solid



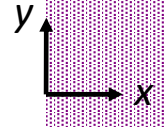
$H, D$ , very large

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1D Heat Transfer: Unsteady State

Initial Condition:

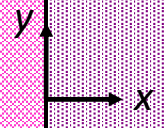
$t < 0$   
 $T = T_o$



$t < 0$   
 $T = T_o$

---

$t \geq 0$   
 $T = T_1$



$t > 0$   
 $T = T(x, t)$

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1D Heat Transfer: Unsteady State

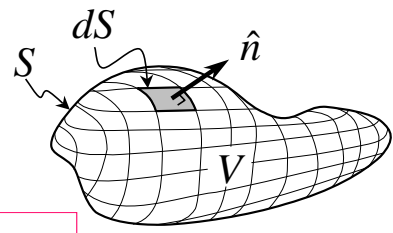
### General Energy Transport Equation

(microscopic energy balance)

As for the derivation of the microscopic momentum balance, the microscopic energy balance is derived on an arbitrary volume,  $V$ , enclosed by a surface,  $S$ .

Gibbs notation:

$$\rho \hat{C}_p \left( \frac{\partial T}{\partial t} + \underline{v} \cdot \nabla T \right) = k \nabla^2 T + S$$



see handout for component notation

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1D Heat Transfer: Unsteady State

### General Energy Transport Equation

(microscopic energy balance)

$$\rho \hat{C}_p \left( \underbrace{\frac{\partial T}{\partial t}}_{\text{rate of change}} + \underbrace{v \cdot \nabla T}_{\text{convection}} \right) = \underbrace{k \nabla^2 T}_{\text{conduction (all directions)}} + \underbrace{S}_{\text{source (energy generated per unit volume per time)}}$$

velocity must satisfy equation of motion, equation of continuity

see handout for component notation

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### Equation of energy

for Newtonian fluids of constant density,  $\rho$ , and thermal conductivity,  $k$ , with source term (source could be viscous dissipation, electrical energy, chemical energy, etc., with units of energy/(volume time)).

CM310 Fall 1999 Faith Morrison

Source: R. B. Bird, W. E. Stewart, and E. N. Lightfoot, *Transport Processes*, Wiley, NY, 1960, page 319.

Gibbs notation (vector notation)

**Note: this handout is on the web:**  
[www.chem.mtu.edu/~fmorriso/cm310/energy2013.pdf](http://www.chem.mtu.edu/~fmorriso/cm310/energy2013.pdf)

$$\left( \frac{\partial T}{\partial t} + v \cdot \nabla T \right) = \frac{k}{\rho \hat{C}_p} \nabla^2 T + \frac{S}{\rho \hat{C}_p}$$

Cartesian (xyz) coordinates:

$$\frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} = \frac{k}{\rho \hat{C}_p} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{S}{\rho \hat{C}_p}$$

Cylindrical (r $\theta$ z) coordinates:

$$\frac{\partial T}{\partial t} + v_r \frac{\partial T}{\partial r} + \frac{v_\theta}{r} \frac{\partial T}{\partial \theta} + v_z \frac{\partial T}{\partial z} = \frac{k}{\rho \hat{C}_p} \left( \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{S}{\rho \hat{C}_p}$$

Spherical (r $\theta$  $\phi$ ) coordinates:

$$\frac{\partial T}{\partial t} + v_r \frac{\partial T}{\partial r} + \frac{v_\theta}{r} \frac{\partial T}{\partial \theta} + \frac{v_\phi}{r \sin \theta} \frac{\partial T}{\partial \phi} = \frac{k}{\rho \hat{C}_p} \left( \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T}{\partial r} \right) + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial T}{\partial \theta} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial^2 T}{\partial \phi^2} \right) + \frac{S}{\rho \hat{C}_p}$$

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1D Heat Transfer: Unsteady State

**Example 1: Unsteady Heat Conduction in a Semi-infinite solid**

A very long, very wide, very tall slab is initially at a temperature  $T_0$ . At time  $t = 0$ , the left face of the slab is exposed to an environment at temperature  $T_1$ . What is the time-dependent temperature profile in the slab? The slab is a homogeneous material of thermal conductivity,  $k$ , density,  $\rho$ , and heat capacity,  $C_p$ .

Newton's law of cooling BC's:

$$|q_x| = hA|T_{bulk} - T_{surface}|$$

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1D Heat Transfer: Unsteady State

Microscopic Energy Equation in Cartesian Coordinates

$$\frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} = \frac{k}{\rho \hat{C}_p} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{S}{\rho \hat{C}_p}$$

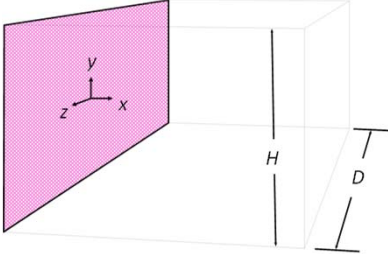
$$\alpha \equiv \frac{k}{\rho \hat{C}_p} = \text{thermal diffusivity}$$

*what are the boundary conditions? initial conditions?*

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1D Heat Transfer: Unsteady State

**Example 7: Unsteady Heat Conduction in a Semi-infinite solid**



Initial Condition:

$t < 0$   $T = T_o$        $t < 0$   $T = T_o$

$t \geq 0$   $T = T_1$        $t > 0$   $T = T(x,t)$

You try.

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1D Heat Transfer: Unsteady State

**Unsteady State Heat Conduction in a Semi-Infinite Slab**

$t < 0$   $T = T_o$        $t < 0$   $T = T_o$

$t \geq 0$   $T = T_1$        $t > 0$   $T = T(x,t)$

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

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

Boundary conditions:

$x = 0, \quad q_x = hA(T - T_1) \quad \forall t > 0$

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

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1D Heat Transfer: Unsteady State

**Unsteady State Heat Conduction in a Semi-Infinite Slab**

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

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

Boundary conditions:

$$x = 0, q_x = hA(T - T_1) \quad \forall t > 0$$

$$x = \infty, T = T_o \quad \forall t \text{ "for all t"}$$

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1D Heat Transfer: Unsteady State

**Unsteady State Heat Conduction in a Semi-Infinite Slab**

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

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

Boundary conditions:

$$x = 0, q_x = hA(T - T_1) \quad \forall t > 0$$

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

**The solution is obtained by combination of variables.**

$$\beta \equiv \frac{h\sqrt{\alpha t}}{k} \quad \zeta \equiv \frac{x}{2\sqrt{\alpha t}}$$

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1D Heat Transfer: Unsteady State

**Unsteady State Heat Conduction in a Semi-Infinite Slab**

**Solution:**

$$\frac{T - T_0}{T_1 - T_0} = \text{erfc } \zeta - e^{\beta(2\zeta + \beta)} \text{erfc}(\zeta + \beta)$$

$$\beta \equiv \frac{h\sqrt{\alpha t}}{k} \quad \zeta \equiv \frac{x}{2\sqrt{\alpha t}}$$

Geankoplis 4<sup>th</sup> ed., eqn 5.3-7, page 363

**complementary error function of y**  $\text{erfc}(y) \equiv 1 - \text{erf}(y)$

**error function of y**  $\text{erf}(y) \equiv \frac{2}{\sqrt{\pi}} \int_0^y e^{-(y')^2} dy'$

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1D Heat Transfer: Unsteady State Heat Conduction in a Semi-Infinite Slab

**Solution:**

$$\frac{T - T_0}{T_1 - T_0} = \text{erfc } \zeta - e^{\beta(2\zeta + \beta)} \text{erfc}(\zeta + \beta)$$

$$\beta \equiv \frac{h\sqrt{\alpha t}}{k} \quad \zeta \equiv \frac{x}{2\sqrt{\alpha t}}$$

Geankoplis 4<sup>th</sup> ed., eqn 5.3-7, page 363

**complementary error function of y**  $\text{erfc}(y) \equiv 1 - \text{erf}(y)$

**error function of y**  $\text{erf}(y) \equiv \frac{2}{\sqrt{\pi}} \int_0^y e^{-(y')^2} dy'$

To make this solution easier to use, we can plot it.

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1D Heat Transfer: Unsteady State Heat Conduction in a Semi-Infinite Slab

$$t < 0$$

$$T = T_o$$

$$t < 0$$

$$T = T_o$$

$$t \geq 0$$

$$T = T_1$$

$$t > 0$$

$$T = T(x,t)$$

**This:**

$$\frac{T - T_o}{T_1 - T_o} = \text{erfc } \zeta - e^{\beta(2\zeta + \beta)} \text{erfc}(\zeta + \beta)$$

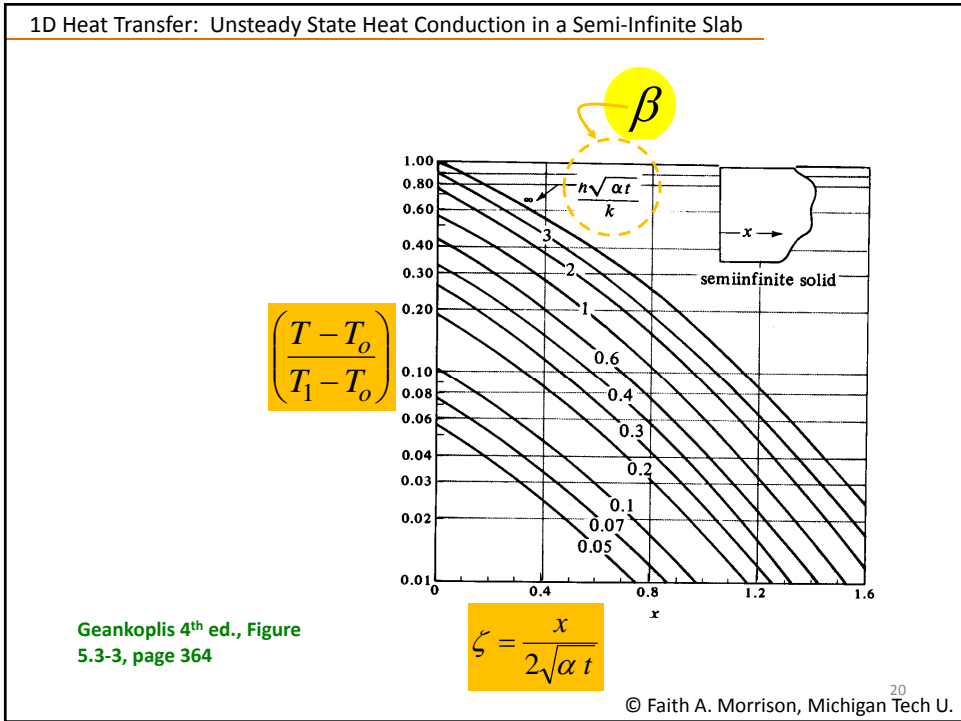
**Versus this:**  $\zeta \equiv \frac{x}{2\sqrt{\alpha t}}$

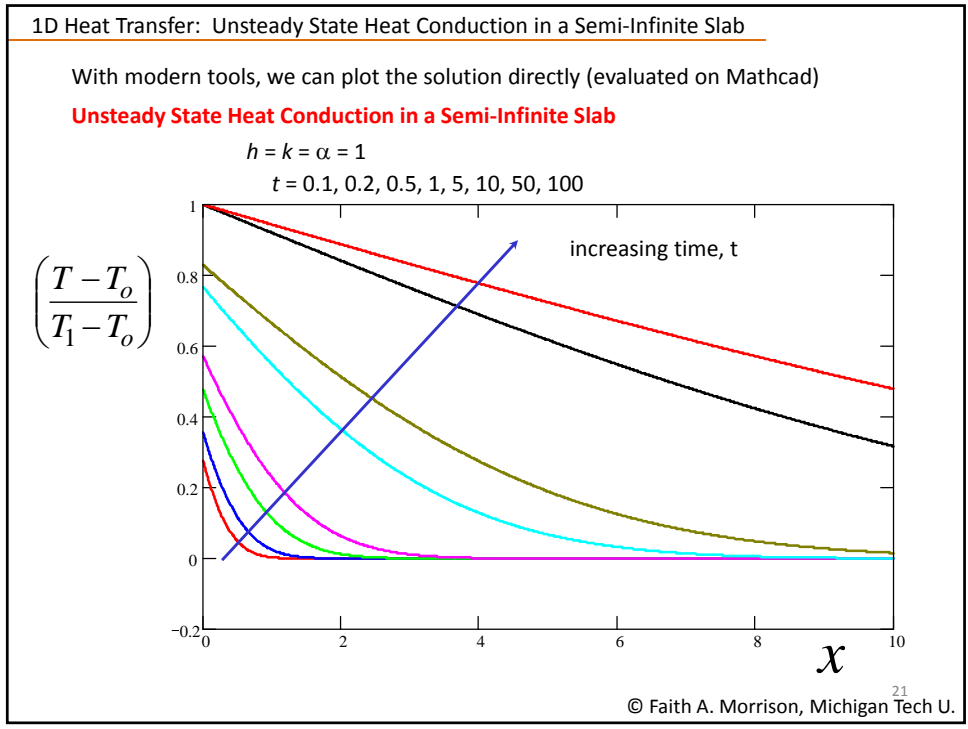
To make this solution easier to use, we can plot it.

**At various values of this:**

$$\beta \equiv \frac{h\sqrt{\alpha t}}{k}$$

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1D Heat Transfer: Unsteady State Heat Conduction in a Semi-Infinite Slab

How could we use this solution?

**Example:** 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 underground? Use the following physical properties:

$$h = 2.0 \frac{BTU}{h \text{ ft}^2 \text{ } ^\circ F}$$

$$\alpha_{soil} = 0.018 \frac{\text{ft}^2}{h}$$

$$k_{soil} = 0.5 \frac{BTU}{h \text{ ft } ^\circ F}$$

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1D Heat Transfer: Unsteady State Heat Conduction in a Semi-Infinite Slab

$$\frac{T - T_0}{T_1 - T_0} = \operatorname{erfc} \zeta - e^{\beta(2\zeta + \beta)} \operatorname{erfc}(\zeta + \beta)$$

$$\zeta \equiv \frac{x}{2\sqrt{\alpha t}}$$

$$\beta \equiv \frac{h\sqrt{\alpha t}}{k}$$

Both  $\zeta$  and  $\beta$  depend on time

$T_0 = ?$

$T_1 = ?$

$T = ?$

$\frac{T - T_0}{T_1 - T_0} = ?$

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1D Heat Transfer: Unsteady State Heat Conduction in a Semi-Infinite Slab

(Iterative solution)

Geankoplis 4<sup>th</sup> ed., Figure 5.3-3, page 364

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1D Heat Transfer: Unsteady State Heat Conduction in a Semi-Infinite Slab

$$\frac{T - T_0}{T_1 - T_0} = \operatorname{erfc} \zeta - e^{\beta(2\zeta + \beta)} \operatorname{erfc}(\zeta + \beta)$$

$$t < 0$$

$$T = T_0$$

$$t > 0$$

$$T = T(x, t)$$

Answer:  
 $t = 480 \text{ hours} \approx 20 \text{ days}$

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1D Heat Transfer: Unsteady State

**Example 8: Unsteady Heat Conduction in a Finite-sized solid**

- The slab is tall and wide, but of thickness  $2H$
- Initially at  $T_0$
- at time  $t = 0$  the temperature of the sides is changed to  $T_1$

$t > 0$

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1D Heat Transfer: Unsteady Heat Conduction in a Finite Solid

**Unsteady State Heat Transfer**

Use same microscopic energy balance eqn as before.

$$\rho \hat{C}_p \underbrace{\left( \frac{\partial T}{\partial t} + \underbrace{\underline{v} \cdot \nabla T}_{\text{convection}} \right)}_{\text{rate of change}} = \underbrace{k \nabla^2 T}_{\text{conduction (all directions)}} + \underbrace{S}_{\text{source (energy generated per unit volume per time)}}$$

see handout for component notation

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1D Heat Transfer: Unsteady Heat Conduction in a Finite Solid

Microscopic Energy Equation in Cartesian Coordinates

$$\frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} + v_z \frac{\partial T}{\partial z} = \frac{k}{\rho \hat{C}_p} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{S}{\rho \hat{C}_p}$$

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

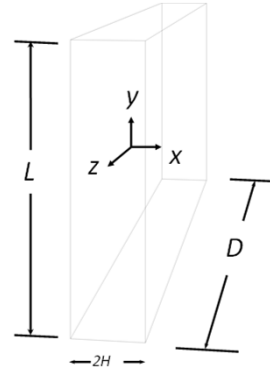
what are the boundary conditions? initial conditions?

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## 1D Heat Transfer: Unsteady Heat Conduction in a Finite Solid

**Example 8: Unsteady Heat Conduction in a Finite-sized solid**

You try.

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## 1D Heat Transfer: Unsteady Heat Conduction in a Finite Solid

## Unsteady State Heat Conduction in a Finite Slab

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

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

Boundary conditions:

$$\left. \begin{array}{l} x = 0, \quad T = T_1 \\ x = 2H, \quad T = T_1 \end{array} \right\} \forall t > 0$$

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1D Heat Transfer: Unsteady Heat Conduction in a Finite Solid

**Q:** How can two completely different situations give the same governing equation?  
**A:** The boundary conditions make all the difference

For more solutions to this equation see Carslaw and Jeager, *Conduction of Heat in Solids*, 2nd Edition, Oxford, 1959

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1D Heat Transfer: Unsteady Heat Conduction in a Finite Solid

Unsteady State Heat Conduction in a Finite Slab

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

**The solution is obtained by separation of variables.**

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

Boundary conditions:  $\left. \begin{matrix} x = 0, & T = T_1 \\ x = 2H, & T = T_1 \end{matrix} \right\} \forall t > 0$

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## 1D Heat Transfer: Unsteady Heat Conduction in a Finite Solid

Unsteady State Heat Conduction in a Finite Slab: solution by separation of variables

$$\text{Let } Y \equiv \left( \frac{T_1 - T}{T_1 - T_o} \right) \quad \frac{\partial Y}{\partial t} = \alpha \left( \frac{\partial^2 Y}{\partial x^2} \right)$$

$$\text{Guess: } Y = X(x)\Theta(t)$$

Initial condition:

$$t = 0, T = T_o \quad \forall x \Rightarrow Y = 1$$

Boundary conditions:

$$\left. \begin{array}{l} x = 0, \quad T = T_1 \Rightarrow Y = 0 \\ x = 2H, \quad T = T_1 \Rightarrow Y = 0 \end{array} \right\} \quad \forall t > 0$$

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## 1D Heat Transfer: Unsteady Heat Conduction in a Finite Solid

Unsteady State Heat Conduction in a Finite Slab: soln by separation of variables

$$Y = X(x)\Theta(t) \quad \frac{\partial Y}{\partial t} = \alpha \left( \frac{\partial^2 Y}{\partial x^2} \right)$$

$$\frac{\partial Y}{\partial t} = \frac{\partial}{\partial t} (X(x)\Theta(t)) = X(x) \frac{d\Theta(t)}{dt}$$

$$\frac{\partial Y}{\partial x} = \frac{\partial}{\partial x} (X(x)\Theta(t)) = \frac{dX(x)}{dx} \Theta(t)$$

$$\frac{\partial^2 Y}{\partial x^2} = \frac{d^2 X(x)}{dx^2} \Theta(t)$$

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1D Heat Transfer: Unsteady Heat Conduction in a Finite Solid

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

Substituting:  $X(x) \frac{d\Theta(t)}{dt} = \alpha \frac{d^2 X(x)}{dx^2} \Theta(t)$

The function of two variables is separable into two functions of one variable.

$$\underbrace{\frac{1}{\Theta(t)} \frac{d\Theta(t)}{dt}}_{\text{function of time (t) only}} = \alpha \underbrace{\frac{1}{X(x)} \frac{d^2 X(x)}{dx^2}}_{\text{function of position (x) only}} \Rightarrow = \lambda$$

constant

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1D Heat Transfer: Unsteady Heat Conduction in a Finite Solid

Separates into two ordinary differential equations:

$$\frac{1}{\Theta(t)} \frac{d\Theta(t)}{dt} = \lambda$$

$$\alpha \frac{1}{X(x)} \frac{d^2 X(x)}{dx^2} = \lambda$$

The function of two variables is separable into two functions of one variable.

Solve.

Apply BCs.

Apply ICs.

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## 1D Heat Transfer: Unsteady Heat Conduction in a Finite Solid

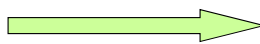
Temperature Profile for Unsteady State  
Heat Conduction in a Finite Slab

$$\left( \frac{T_1 - T}{T_1 - T_o} \right) = \frac{4}{\pi} \left\{ e^{-\frac{\pi^2 \alpha t}{4H^2}} \sin \frac{\pi x}{2H} + \frac{1}{3} e^{-\frac{3^2 \pi^2 \alpha t}{4H^2}} \sin \frac{3\pi x}{2H} + \frac{1}{5} e^{-\frac{5^2 \pi^2 \alpha t}{4H^2}} \sin \frac{5\pi x}{2H} + \dots \right\}$$

Geankoplis 4<sup>th</sup> ed., eqn 5.3-6, p363

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## 1D Heat Transfer: Unsteady State



Microscopic Energy Balance – is the correct physics  
for many problems!

**Tricky step:**

solving for  $T$  field; this can be mathematically difficult

- partial differential equation in up to three variables
- boundaries may be complex
- multiple materials, multiple phases present
- may not be separable from mass and momentum balances

**Strategy:**

- Look up solution in literature
- solve using numerical methods (e.g. *Comsol*)

\*\*\*\* Or \*\*\*\*

- Develop correlations on complex systems by using *Dimensional Analysis*

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**Fluid Mechanics: What did we do?**

- Turbulent tube flow
- Noncircular conduits
- Drag on obstacles

1. Find a simple problem that allows us to identify the physics
2. Nondimensionalize
3. Explore that problem
4. Take data and correlate
5. Solve real problems

**Solve. Real. Problems.**

**Powerful.**

**Works on heat transfer too.**

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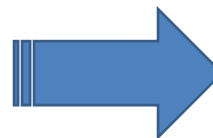
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CM3110  
Transport I  
Part II: Heat Transfer

**MichiganTech**



**More Complex Heat Transfer – Dimensional Analysis**



Professor Faith Morrison  
Department of Chemical Engineering  
Michigan Technological University

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