ChE 313: Applications of Heat and Mass Transfer

Instructor: Prof. Boxin Zhao

University of Waterloo
Department of Chemical Engineering

WELCOME!

COURSE SYLLABUS

Instructor and TA

- **Instructor**
  - Prof. Boxin Zhao
  - Office: E6-2012
  - Tel: x 38666
  - Email: zhaob@uwaterloo.ca

- **Teaching Assistant**
  - Hamad Nasir;
  - Email: h24nasir@uwaterloo.ca

Lectures

- **Lectures:**

  Tuesdays, 10:30am – 12:20pm, AL-208, starting on Jan 9

  Thursdays, Thursdays, 10:30am – 11:20am, MC -4060

- Outline/notes for each lecture will be posted on the Learn before the lectures.

- You are encouraged to take your own notes.

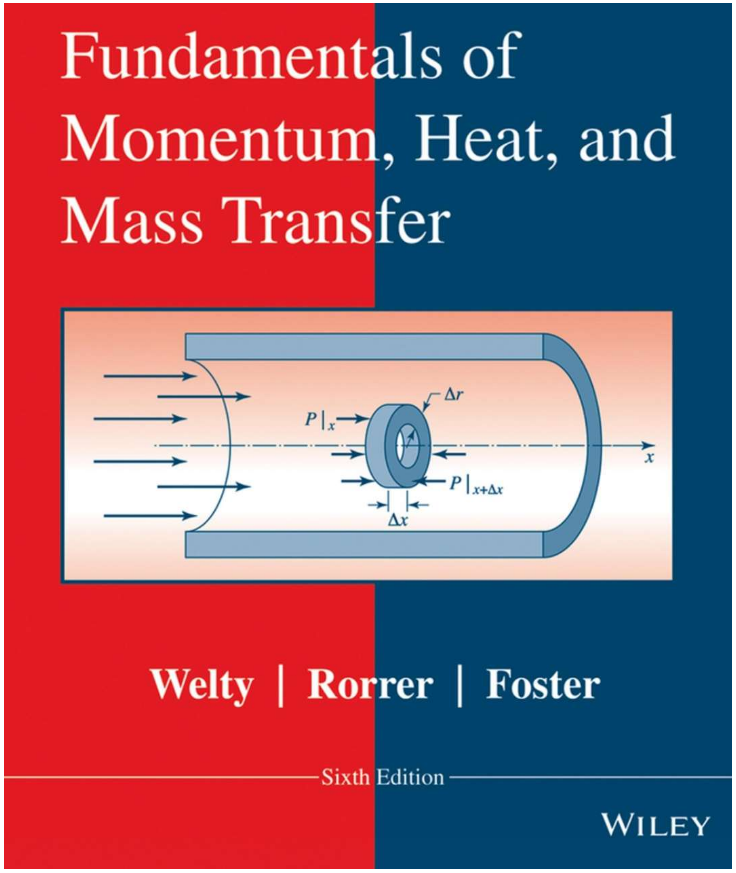
Tutorials and Office Hour

- **Tutorials**: Thursdays, 11:30am – 12:20pm, MC -4060, starting in the 2nd week (Note that we will have a lecture in the tutorial section in the first week.)
  - Give further practice in understanding and applying course materials
  - About 4-5 quizzes

- **Office Hour**: Tuesdays, 9:30pm – 10:20am
  - starting in the 2^{nd} week
  - Note: please come prepared with specific questions.

Textbook

Fundamentals of Momentum, Heat and Mass Transfer, Welty, Rorrer, Foster, sixth Edition, Wiley. (**Primary Textbook**)



Fundamentals of Heat and Mass Transfer, Incropera, DeWitt, Bergman, and Lavine, Sixth Edition (2007), Wiley. (Optional)

Exams/quizzes/assignments

- Tests are open book in that you may consult your textbook, course notes, and materials posted in the course LEARN site.
- Use of any other resource (including file-sharing services such as chegg.com, coursehero.com, stackexchange.com, ...) is prohibited.
- You may not communicate directly or indirectly with any person except the course instructor.
- **Assignments/Quizzes: Submit in the classroom**

Bonus case studies

- Voluntary case studies of Heat and Mass Transfer (e.g. daily life experience, particular industrial scenarios)

- To encourage students to think critically and energize the learning/teaching environment, each student can make a voluntary in-class presentation of their case studies (1-2min), starting after the mid-term exam (email <u>two ppt slides</u> to Instructor one day ahead)

- A bonus of 2 marks for the in-class presentations

Assessments and Marking Scheme

Item	% Total Mark	Comments
Assignments	10	About 6 assignments*
Quizzes/Tutorials	10	About 4 quizzes**
Midterm	25	
Final	55	
In-class presentation	2	Bonus mark***

Note:

* Equal marks for each assignment
** Equal marks for each quiz
***The total mark is capped at 100 even though your mark might be above 100 due to the bonus.

Posting and Submission

- Assignment due date: Jan 23, Feb 6, Feb 13, Mar 7, Mar 19, Apr 4 (will be **posted on Learn** in a week before the due date, **submit in the class**): otherwise, it will be announced in the class

- Quizzes: Jan 25, Feb 8, Mar 14, Mar 28; otherwise, it will be announced in the class.

- Reading week: Feb 17, 2024 to Feb 25, 2024

- Midterm Exam Date: Feb 29, 2024

- Final Exam Date: Scheduled by the Registrar's Office

Plagiarism and Academic Offences

- Though you are encouraged to work in groups, you must present your own work in assignments and quizzes.
- There will be a **zero tolerance** approach taken to cases of plagiarism and other offences.
- For more information, please refer to policy 71:

  http://www.adm.uwaterloo.ca/infosec/Policies/policy71.htm

Course Outline

Convective heat transfer. Analysis of convective heat transfer in external flows using boundary layer approach. Analysis of convective heat transfer in internal flows. Empirical correlations for convective heat transfer. Heat exchanger design. **Convective mass transfer.** Empirical correlations for convective mass transfer. Mass transfer at fluid-fluid interfaces. Analogy between heat-transfer, mass transfer and momentum. Dimensional analysis. Simultaneous heat and mass transfer operations.

Prereq: 3B Chemical Engineering

Course Contents

Heat Transfer

1. Introduction to Heat Transfer and Review of Conductive Heat Transfer
2. Convective Heat Transfer (Text Ch.19)
3. Convective Heat-Transfer Correlations (Text Ch.20-21)
4. Heat Exchangers (Text Ch.22)

Mass Transfer

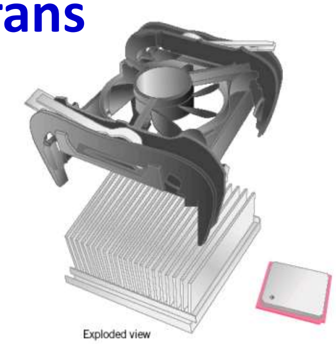
1. Introduction to Mass Transfer and Review of Molecular Diffusion
2. Convective Mass Transfer (Text Ch. 28-29)
3. Convective Heat-Transfer Correlations (Text Ch 30)
4. Mass Exchangers (Text Ch.31)

Learning Outcomes

Reactor

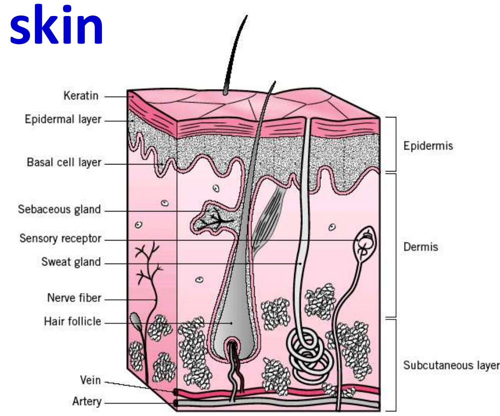
After successful completion of this course, students will be able to:

CPU w/ fans



- *Identify and solve* heat and mass transfer problems relevant to technology ad society
- Analyze boundary layer flows, the relative thicknesses of the thermal and hydrodynamic boundary layers and their effect on estimation of the convective heat transfer coefficients.
- *Analyze and estimate convective heat transfer coefficients* for internal and external flows

Human skin

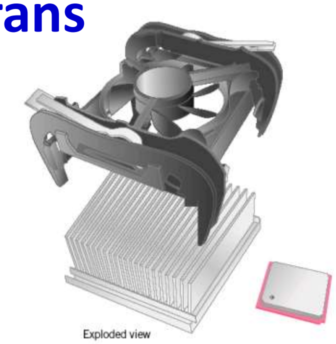


Learning Outcomes

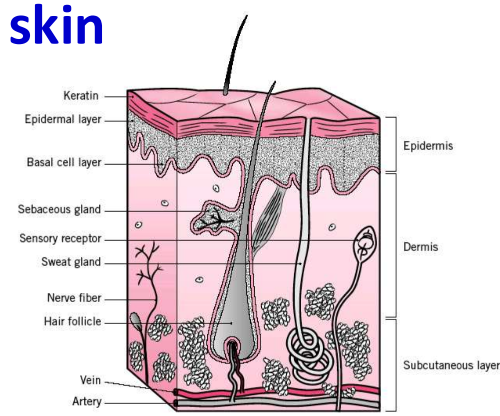
- *Apply correlations for convective heat transfer coefficients* in applications involving phase change such as boiling and condensation.
- *Analyze and design heat transfer equipment* (e.g. double pipe heat exchangers, shell and tube heat exchangers) used in process plants.
- *Evaluate mass transfer problems* by analogy to heat transfer.
- *Analyze and design mass transfer equipment* such as packed columns.

Reactor

CPU w/ fans



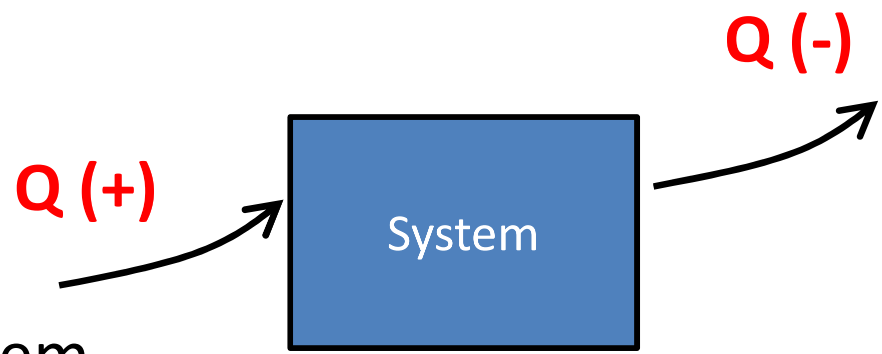
Human skin



Lecture notes 1
Introduction to heat transfer

Fundamentals of Heat Transfer

- Heat Transfer is the transfer of thermal energy due to a spatial temperature difference.



Heat flows
into the system
- Energy input

Heat flows
out the system
- Energy output

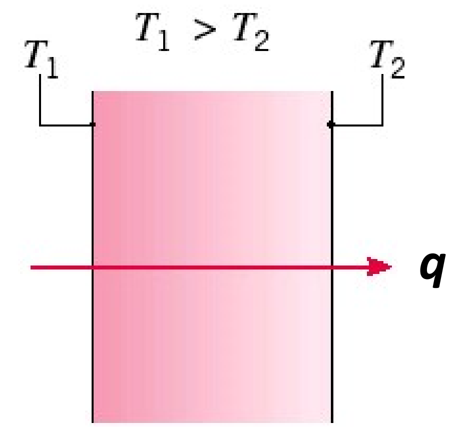
Thermodynamics: “Energy can neither be created nor destroyed.”

Heat Transfer: Modes of the heat transfer and heat transfer rate.

Modes of Heat Transfer

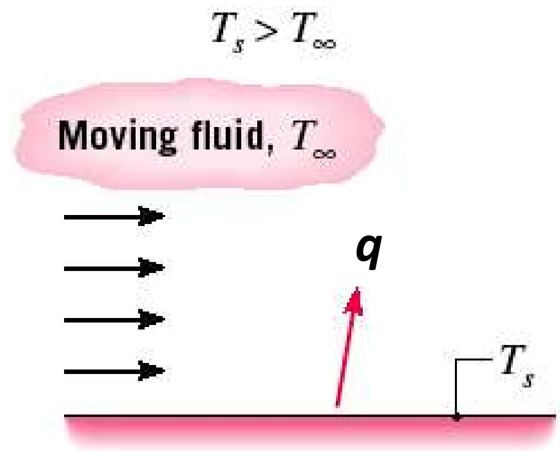
A. Conduction: heat transfer occurring across a stationary medium.

(A)



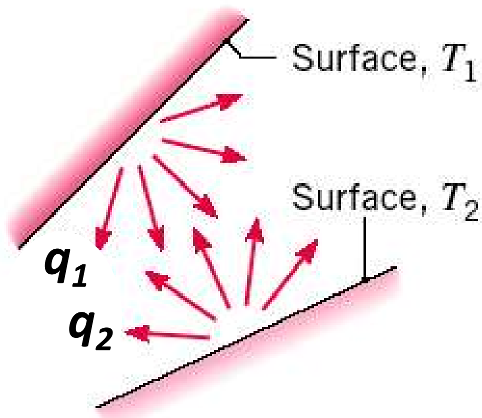
B. Convection: heat transfer occurring between a surface and a moving fluid

(B)



C. Thermal radiation: heat transfer in the absence of an intervening medium. (All surfaces emit energy in the form of electromagnetic waves.)

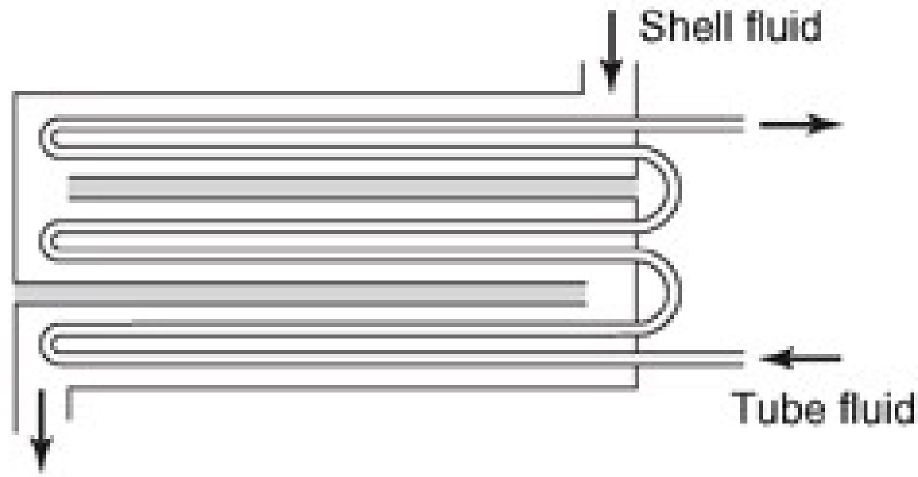
(C)



Heat Transfer Problem

- Determination of the heat transfer rate through analysis of the modes of heat transfer and the development of relations or correlations

- The rate of heat transfer, q (W)
  - Heat exchanger area, A
  - The inlet and outlet temperature difference, ΔT
  - Overall heat transfer coefficient , U

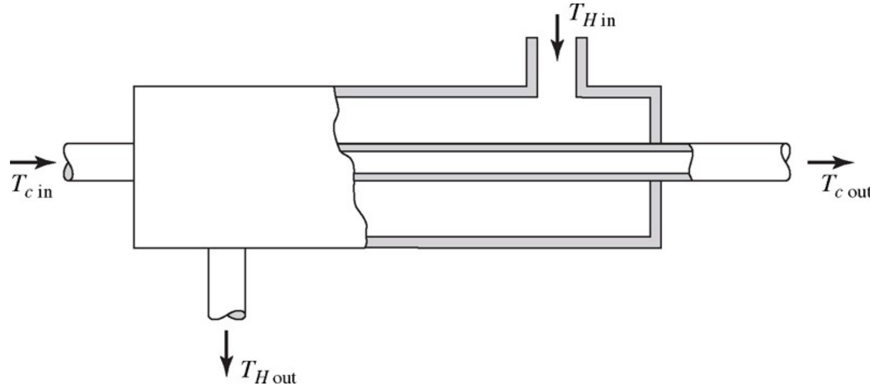


Performance or design equation of heat exchangers

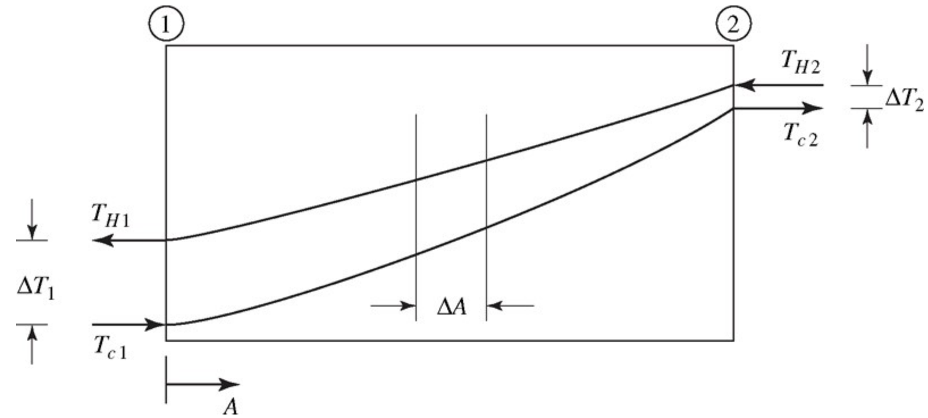
$$q \sim UA\Delta T$$

Conceptual Analysis

- Modes of Heat Transfer - the U term
  - Convection from shell fluid to the outside surface of tube wall
  - Conduction across the tube wall
  - Convection from the inside surface of the tube wall to the tube fluid



- Temperature difference, the ΔT term
  - ΔT changes with distance
  - Log-mean temperature difference



- Heat exchanger area, the A term
  - the outside surface area of the tube
  - The inside surface area of the tube
  - The number of pass

$$q = UA\Delta T_{lm}$$

Heat Transfer

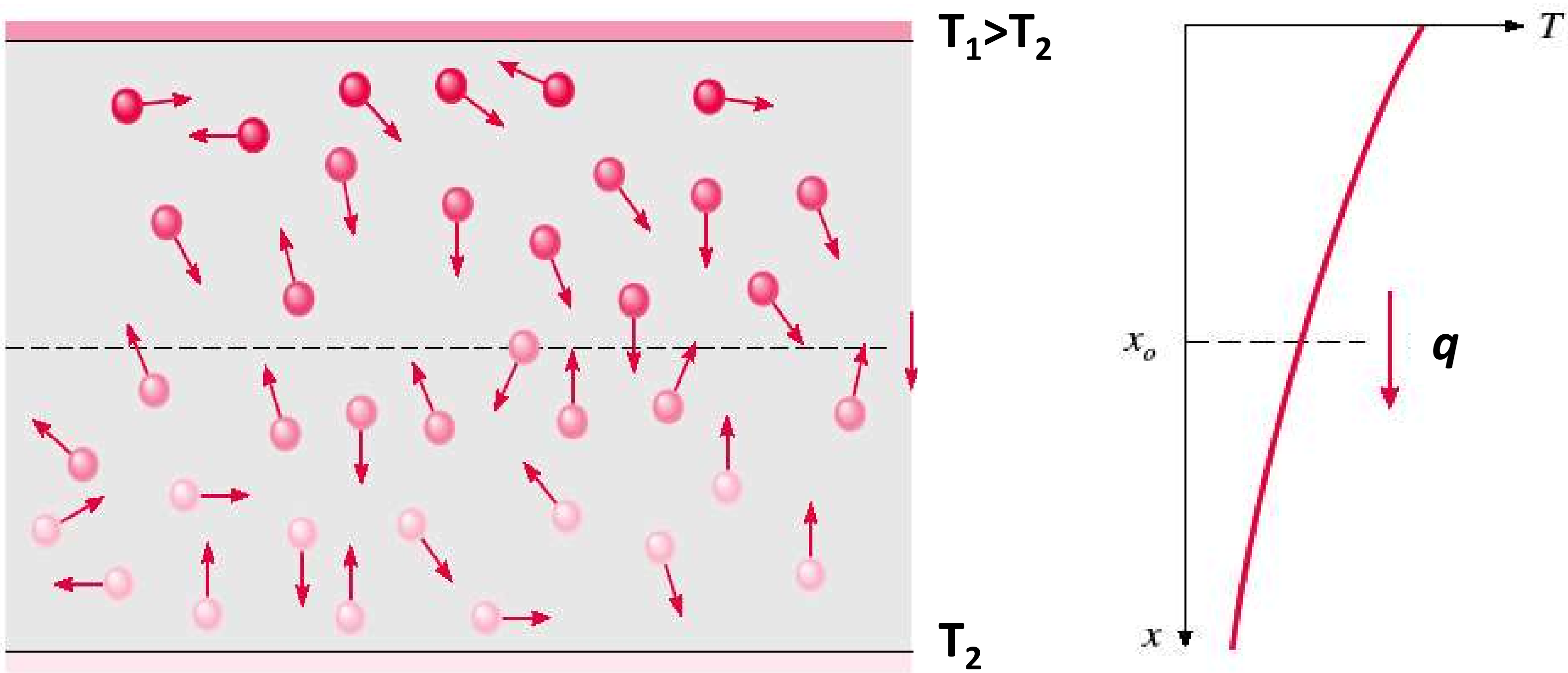
- **Review of Conductive Heat Transfer (Text Ch. 15-18)**
  - Fourier's law of heat conduction
  - Fourier field equation
  - Conductive thermal resistance

- **Convective Heat Transfer (Text Ch.19-22)**
  - Thermal boundary layer
  - Analysis of convective heat transfer in external and internal flows and equations for heat transfer coefficient
  - Empirical correlations for convective heat transfer
  - Design of double-pipe and shell-tube heat exchangers

Review of Conductive Heat Transfer

Physical Origins of Conduction

- Atomic or molecular activity
- Transfer of energy from the more energetic particles to the less energetic particles of a substance
  - Random motion(translational, rotational and vibrational motions for gas and liquid molecules; lattice motions for solids)
  - Collisions



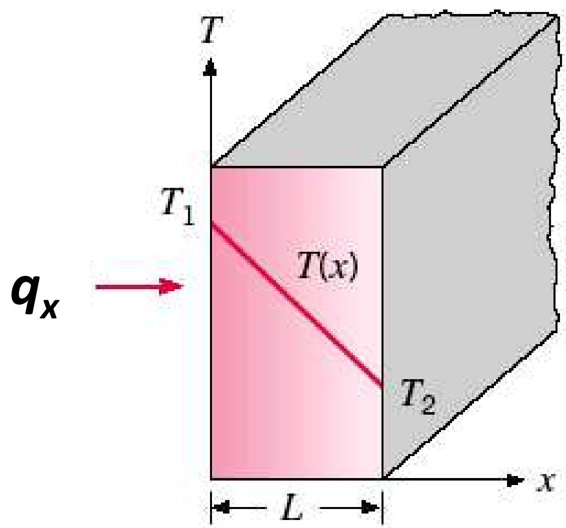
Rate of Conductive Heat Transfer

- Fourier Rate equation (Fourier's first law of heat conduction)

$$\frac{q}{A} = -k\nabla T = -k\left(\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial z}\right) \qquad (15\text{-}2)$$

Heat Flux **Thermal conductivity** **Temperature gradient**

One-dimensional heat transfer by conduction

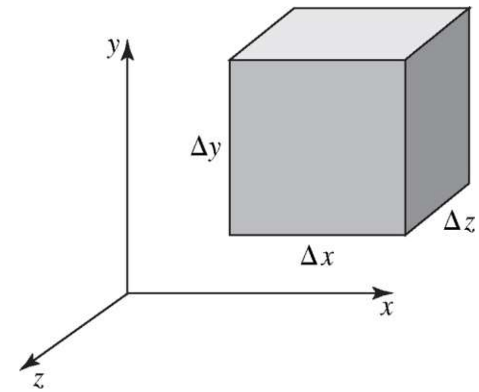


$$\frac{q_x}{A} = -k\frac{\partial T}{\partial x}$$

Differential Energy Equation

- Energy equation

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot k \nabla T + \dot{q} \qquad \text{(16-16)}$$



ρ - fluid density
c_p - heat capacity
$\dot{q}$ - thermal energy generation rate

- With constant k

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c_p} \nabla^2 T + \frac{\dot{q}}{\rho c_p}$$

$$a = \frac{k}{\rho c_p}$$

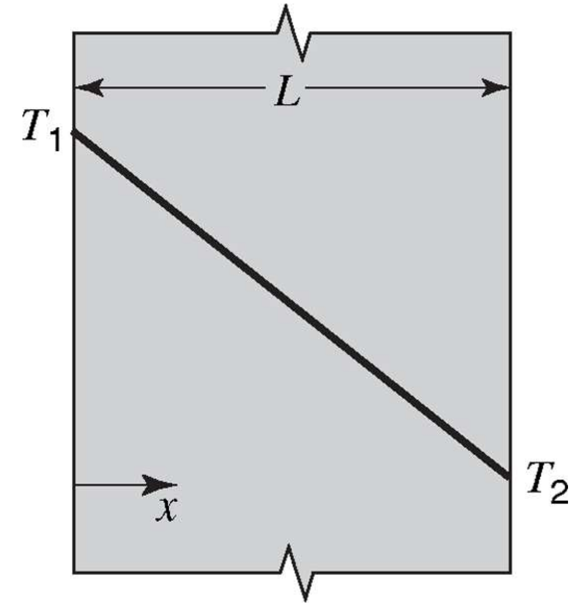
Thermal diffusivity

- When no heat sources

$$\frac{\partial T}{\partial t} = a \nabla^2 T$$

Fourier field equation or
Fourier's second law of heat conduction

Steady-state Conduction through a Plane Wall



- The Fourier rate equation
  - one-dimensional equation

$$\frac{q_x}{A} = -k\frac{dT}{dx} \qquad q_x = \frac{kA}{L}(T_1 - T_2)$$

- Energy equation

$$\frac{\partial T}{\partial t} = a\nabla^2 T \Rightarrow \nabla^2 T = 0 \Rightarrow \frac{d^2T}{dx^2} = 0$$

Boundary conditions: x =0 $T=T_1$; x = L $T=T_2$

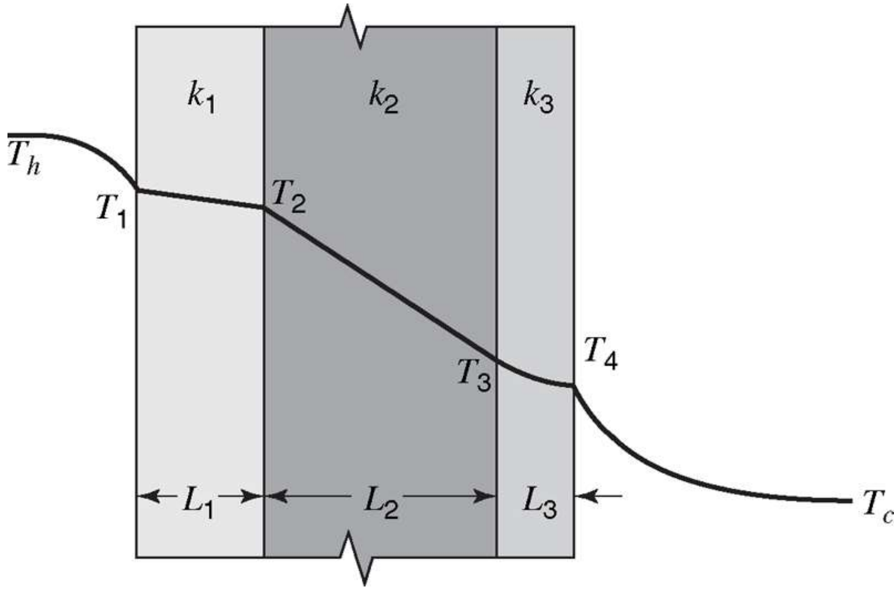
$$T = T_1 - \frac{T_1 - T_2}{L}x$$

Thermal resistance

$$R = \frac{L}{kA} \qquad q_x = \frac{(T_1 - T_2)}{R}$$

Combined Mechanism

- Composite walls and composite thermal resistance
  - Analog of electrical circuit
  - Series and parallel energy-flow paths
- Each temperature difference



$$T_h - T_1 = q_x(1/h_h A) = q_x \cdot R_1$$
$$T_1 - T_2 = q_x(L_1/k_1 A) = q_x \cdot R_2$$
$$T_2 - T_3 = q_x(L_2/k_2 A) = q_x \cdot R_3$$
$$T_3 - T_4 = q_x(L_3/k_3 A) = q_x \cdot R_4$$
$$T_4 - T_c = q_x(1/h_c A) = q_x \cdot R_5$$

(15-15)

$$q_x = \frac{T_h - T_c}{1/h_h A + L_1/k_1 A + L_2/k_2 A + L_3/k_3 A + 1/h_c A} = \frac{T_h - T_c}{\sum R}$$

Unsteady-state Conduction

- Transient processes
  - The process that ultimately reaches steady-state conditions,
  - The process that is operated a relatively short time in a continually changing temperature environment, e.g. metal quenching

- Temperature depends on both time and position

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{\dot{q}}{\rho c_p} \qquad (16\text{-}16)$$

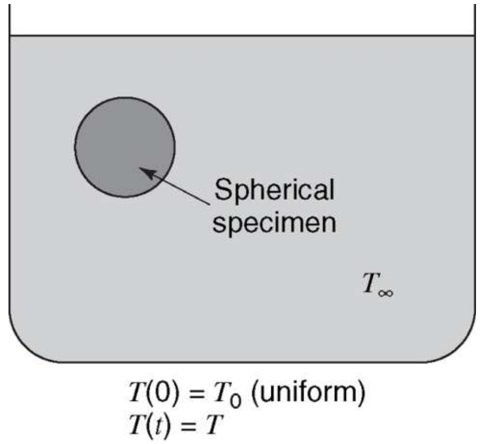
- Solving the equation is often complex.
  - Separation of variables
  - Laplace transformation
  - Numerical methods

Systems with Negligible Internal Resistance

- The temperature within the material varies with time only.
- The transient temperature response is determined by formulating an overall energy balance on the solid.

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{\dot{q}}{\rho c_p} \Rightarrow \rho V c_p \frac{dT}{dt} = hA(T_\infty - T) \qquad \text{(18-4)}$$

$$\frac{T - T_\infty}{T_0 - T_\infty} = \exp\left(\frac{-hAt}{\rho c_p V}\right) = \exp(-B_i F_o) \qquad \text{(18-5)}$$



Bi < 0.1

Lumped Parameter: Biot modulus and Fourier modulus

$$Bi = \frac{hV/A}{k} \qquad \text{(18-7)}$$

$$Fo = \frac{\alpha t}{(V/A)^2} \qquad \text{(18-8)}$$

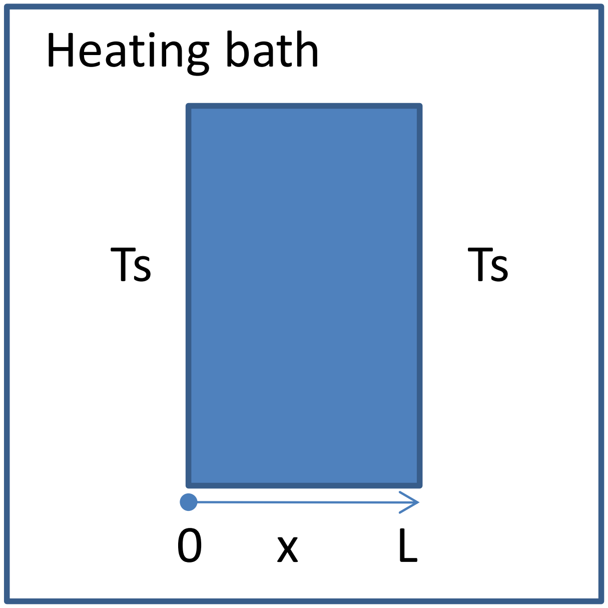
Systems with Negligible Surface Resistance

- Fourier field equation

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{\dot{q}}{\rho c_p} \Rightarrow \frac{\partial T}{\partial t} = \alpha \nabla^2 T \Rightarrow \frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

- Boundary and Initial conditions

$T=T_0(x)$ at $t=0$ for $0 \le x \le L$
$T=Ts$ at $x=0$ for $t>0$
$T=Ts$ at $x=L$ for $t>0$



Heating a body with constant surface temperature

$$\frac{T - T_s}{T_0 - T_s} = \frac{4}{\pi} \sum_{n=1}^{\infty} \frac{1}{n} \sin\left(\frac{n\pi}{L} x\right) e^{(-n\pi/2)^2 Fo} \qquad n = 1, 3, 5 \ldots \qquad (18\text{-}13)$$

- Rate equation

$$q_x = -kA \frac{\partial T}{\partial x}$$

Temperature-time charts

- Solved temperature profiles at the central position for simple geometric shapes

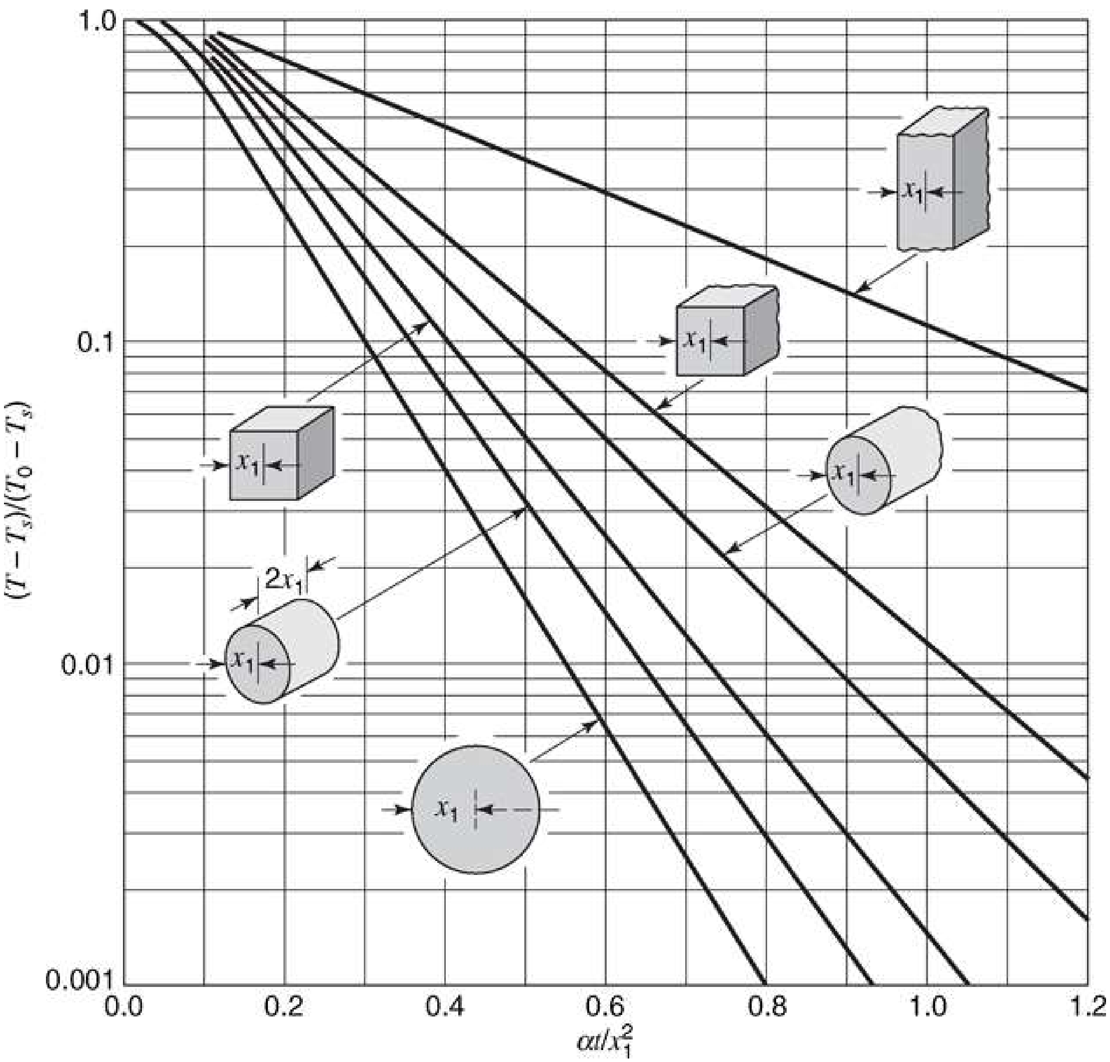


Figure 18.3

Four dimensionless ratios

Unaccomplished temperature change, Y $\quad Y = \dfrac{T_\infty - T}{T_\infty - T_0}$

Relative time, X $\quad X = \dfrac{at}{x_1^2}$

Relative position, n $\quad n = \dfrac{x}{x_1}$

Relative resistance, m $\quad m = \dfrac{k}{hx_1}$