Course Introduction

Larry Caretto
Mechanical Engineering 375

Heat Transfer

January 29-31, 2007

Monday Class

- First class day items: roll, outline, etc.
- Class goals and learning objectives
- Assessment quiz
- Discussion of dimensions and units
  - Physical quantities have dimensions
  - Several units measure same dimension
  - Use SI system of units (meter, kilogram, ...
  - Also use engineering units (feet, pounds ...

2

Wednesday Class

- Definition of heat transfer terms
- Modes of heat transfer and their basic equations
  - Conduction and thermal conductivity
  - Convection and heat transfer coefficient
  - Radiation and Stefan-Boltzmann constant
- Ohm's law analogy: thermal circuits
- Multiple modes of heat transfer

3

Basic Information

- Larry Caretto, Jacaranda (Engineering) 3333, lcaretto@csun.edu, 818.677.6448
- Office hours Monday, Tuesday, Wednesday, and Thursday 1:30 to 2:30 pm; other times by email, phone, drop-in, or appointment
- http://www.csun.edu/~lcaretto/me375
- Yunus A. Çengel, *Heat and Mass Transfer A Practical Approach* (third edition), McGraw-Hill, 2007.

4

Email

- Campus policy requires students to monitor their CSUN email addresses
  - These addresses will be used class email list me375-c@csun.edu
- Setup account and, if desired, forward email to another address
  - https://www.csun.edu/helpdesk/stuact.html
  - https://www.csun.edu/account

5

Course Learning Objectives

- Understand and be able to formulate and solve problems in conduction, convection and radiation heat transfer using basic material properties: thermal conductivity, density, heat capacity, and thermal diffusivity
- solve problems with multiple modes of heat transfer, using heat transfer coefficients and the circuit analogy where appropriate

6

More Learning Objectives

- solve one-dimensional, steady conduction heat transfer problems in various geometries with constant and variable thermal conductivity
- solve one-dimensional, steady conduction heat transfer problems in various geometries with heat sources
- solve multi-dimensional, steady heat transfer problems using shape factors

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Still More Learning Objectives

- be familiar with the partial differential equations used for transient and steady heat transfer in one or more dimensions and be able to apply solutions to these equations to find temperatures
- solve transient heat transfer problems known as "lumped capacity" problems where the main heat transfer resistance is from external convection
- solve transient heat transfer with charts

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Learning Objectives (Almost over)

- understand the important parameters that govern the accuracy of a finite difference solution and be able to use these parameters to obtain accurate computer solutions with software packages
- understand differences: laminar *vs.* turbulent flows; external *vs.* internal flows; and free convection *vs.* forced convection; calculate appropriate dimensionless parameters for each

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Learning Objectives Concluded

- solve convection problems for any flow condition using empirical equations
- solve problems heat exchanger problems using both the U factor and the NTU methods
- use blackbody distribution function and radiation properties (emissivity, transmissivity, and absorbtivity) in solving problems
- use shape factors and the gray body assumption to solve radiation problems

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Thermodynamics

- Usually a prerequisite for ME 375, but not a prerequisite at CSUN
- EE students have choice of ME 370 or ME 375
- Instead of a 370 review this course will use "just-in-time" Thermodynamics
- Cover specific topics as required for course in nature of review

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Class Operation

- Wednesday: quiz (30 minutes) on old topic followed by lecture on new topic
- Monday: student group problem solving to prepare for quiz
  - First quiz is on February 7
- Reading assigned for new topic and lecture presentations available on web
- Homework with solutions posted as-signed, but not collected, for quiz date

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Quizzes

- Twelve during the semester
- Based on group work and homework
  - Problems will be similar, but not exactly the same as group work and homework
- Count ten highest quiz grades for final
  - No makeup quizzes; final quiz grade based only on quizzes taken if fewer than ten
- First four closed book; remainder use sheet of equations from web site

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Grading

• Quiz grades	35%
• Midterm (March 28)	20%
• Final (May 23)	35%
• Design project (May 26)	10%

- Plus/minus grading will be used
- Grading criteria in course outline
- No make-up quizzes or exams

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See the Course Outline

- Download from course web site
  - http://www.csun.edu/~lcaretto/me375
- Contains lecture schedule and homework assignments
- Also read information on the following items
  - Class participation and courtesy
  - Collaboration versus plagiarism: students found cheating receive F grade in course
- Students are responsible for changes to outline announced in class

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Design Project

- Involves use of heat transfer software
- Due at end of semester
- Details to be provided later

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Galileo Galilei

(1564-1642)

You cannot teach a man anything; you can only help him find it within himself.

http://space.about.com/od/astronomyhistory/a/galileoquotes.htm

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Goals for this Course

- My goal is to help all students find within themselves sufficient knowledge of heat transfer so that they will all get an A grade in the course
- What is your goal for this course?
- What will we do to help us achieve our mutual goals?

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How to get your A

- Spend six to ten hours per week outside class studying for the course
- Prepare for lecture and be ready to ask questions
  - Read the assigned reading before class
  - Download, print, and review the lecture presentations before class
    - Use presentations instead of writing notes
    - Listen to the lecture and ask questions
    - Write additional notes on presentations

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How to Get your A, Part II

- Study with fellow students and try to answer each other's questions
- Do the homework as well as you can before reviewing the on-line solutions
- Contact me by email, telephone or office visits to ask questions
- Work with a group of classmates to study course material and help each other with homework

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What I will do to help

- Arrive at class a few minutes early to answer any questions you may have
- Give lectures that stress application of basics to problem solving
- Return quizzes and exams promptly so that you can learn from your errors
- Be available for questions in my office (visit or telephone) or email
  - Send entire class emails as appropriate

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Preliminary Assessment

- Designed to help instruction
- One set of questions on student background
- Second set of questions is ungraded quiz
- Take about 10 minutes for this assessment
- Hand yours in when finished
  - Will call time when most students are done

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Dimensions and Units

- Any physical quantity has a unique dimension: e.g., mass, length, time, …
- Several units may be available for any dimension
  - Length is measured in meters, feet, miles, fathoms, furlongs, yards, light-years, etc.
  - You cannot measure length in units with the dimension of mass

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Systems of Units

- Arbitrary units for fundamental dimensions, e.g. mass (M), length (L), time (T), and temperature (Θ).
- Units for other physical quantities from the physical relations to quantities with fundamental units
  - Velocity dimensions are length/time.
  - Acceleration dimensions are length/time^2,
  - Force dimension of (mass)(length)/(time)^2

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More Dimensions

- Pressure = force per unit area
  = (force) / $(length)^2$
  = (mass) (length) / $[(time)^2(length)^2]$
  = (mass) / $[(time)^2(length)]$ or $MT^{-2}L^{-1}$
- Common dimensions for energy terms are $(mass)(length)^2/(time)^2$ or ML^2T^{-2}
  - Work = force times distance
    = (force)(length)
    = $(mass)(length)^2/(time)^2$ or ML^2T^{-2}
  - Kinetic energy = $mV^2/2$
    = $(mass)(velocity)^2$
    = $(mass)(length)^2/(time)^2$ or ML^2T^{-2}

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Still More Dimensions

- Another energy term
  - Potential energy = mgh = (mass)(acceleration)(length) = $(mass)(length)^2/(time)^2$ or ML^2T^{-2}
- Power = (energy)/(time)
  = (mass) $(length)^2$ / $(time)^3$ or ML^2T^{-3}
- In thermodynamics work is PdV
  - This is like Fdx where P = F/A and dV = Adx (A is area)
  - PdV dimensions are $(length)^3$(force)/(area) which also is $(mass)(length)^2/(time)^2$

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SI Units

- Basic definitions for fundamental units
  - Mass: kilogram (kg) = international prototype
  - Time: second (s) = time for 9 192 631 770 periods of radiation from Cs^{133}
  - Length: meter (m) = length light travels in 1/299 792 458 of a second
  - Temperature: kelvin (K) = 1/273.16 of the triple point of water
  - Current: ampere (A) defined in terms of electrostatic force

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Other Units

- Light intensity and molar units
- Units for velocity and acceleration are m/s and m/s^2
- Units for force are $kg\cdot m/s^2$
  - 1 newton (N) = 1 $kg\cdot m/s^2$
- Units for energy are $kg(m/s)^2 = N\cdot m$
  - 1 joule (J) = 1 $N\cdot m$ = 1 $kg\cdot m^2/s^2$

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Still More Units

- Power: (energy)/(time) = joules/second
  - 1 watt (W) = 1 J/s = 1 $N\cdot m/s$ = 1 $kg\cdot m^2/s^3$
- Pressure: (force)/(area) = newtons per square meter
  - 1 pascal (Pa) = 1 N/m^2 = 1 $kg/(m\cdot s^2)$
  - Atmospheric pressure = 101.325 kPa
- Note that Sir Isaac Newton has a capital N; 1 newton of force does not, unless it is abbreviated as 1 N (true for all units named after individuals)

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Some Prefixes

pico, p	nano, n	micro, μ	milli, m
10^{-12}	10^{-9}	10^{-6}	10^{-3}
tera, t	giga, g	mega, M	kilo, k
10^{12}	10^{9}	10^{6}	10^{3}

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Temperature Units

- Fundamental unit is the kelvin (K) giving absolute temperature
  - Zero kelvin is lowest possible temperature
- Common unit is the Celsius degree (°C)
- K = °C + 273.15
- Common engineering unit is the Fahrenheit degree – °F = 1.8*(°C) + 32
- Absolute temperature is rankine (R)
  - R = °F + 459.69 = 1.8 K

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Temperature Difference

- If $T_2 - T_1$ = 10°C what is $T_2 - T_1$ in
  - kelvins 10 K
  - degrees Fahrenheit 18°F
  - rankine 18 R
- Basic rules
  - Temperature differences have the same numeric values in kelvins and celsius
  - Temperature differences have the same numeric values in fahrenheit and rankine

$$\Delta T(^oF) = 1.8\Delta T(^oC)$$

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Engineering Units

- Second is the basic unit of time
- The foot = 0.3048 m (exactly) is the basic unit of length
- Pound is confusing because it is used to represent two dimensions
  - Mass: pound-mass (lb_m = 0.453592 kg)
  - Force: pound force ($lb_f = 32.174\ lb_m \cdot ft/s^2$)
    - What is SI equivalent for pound force?

1 lb_f = 4.4482 N

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More Engineering Units

- pressure in lb_f/in^2 (psia) or lb_f/ft^2 (psfa)
  - The final "a" means absolute pressure not gage (measured relative) pressure
- foot-pound is work (energy unit)
- British thermal unit (Btu = 778.16 ft-lb_f)
- Horsepower as power unit
  - 1 hp·hr = 2,545 Btu = 1.98×10^6 ft·lb_f
  - 1 kW·hr = 3,412 Btu

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Calculating Units

- What is kinetic energy of a 100 lb_m mass moving at 10 ft/s
- $mV^2/2 = (100\ lb_m)(10 ft/s)^2 /2 = 5000 lb_m \cdot ft \cdot s^{-2}$
- Unit conversion

$$KE = \frac{(100\ lb_m)}{2}\left(\frac{10\ ft}{s}\right)^2 \frac{lb_f \cdot s^2}{32.174\, lb_m \cdot ft} = 165.4\ ft \cdot lb_f$$

- Note algebraic cancellation of units

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Calculating Units II

- What is the change in potential energy when a mass of 100 kg is raised a distance of 5 m?
- Do this for a location where the local value of g = 2 m/s²

$$PE = mgh = (100\ kg)\frac{2\ m}{s^2}(5\ m)\frac{N \cdot s^2}{1\ kg \cdot m}\frac{1\ J}{N \cdot m} = 1000\ J$$

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Units quiz

- What is the change in potential energy when a mass of 200 lb_m is raised a distance of 15 ft?
- Do you need more data to answer this question?
- What is g? Use 5 ft/s^2 for this problem

$$PE = mgh = (200\ lb_m)\frac{5\ ft}{s^2}(15\ ft)\frac{lb_f \cdot s^2}{32.174\ lb_m \cdot ft} = 466.2\ ft \cdot lb_f$$

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Another Quiz

- Some European engineering calculations use the kilogram-force, defined in the same way as the pound force and measure pressure in kg_f/cm^2
- What exactly is the definition of a kg_f?
- How many newtons are in a kg_f?
- How many pascals are in a kg_f/cm^2?

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Solutions to Another Quiz

- One kg_f is the force required to accelerate 1 kg at an acceleration of standard gravity, g = 9.8067 m/s^2

$$1\,kg_f = 1\,kg\frac{9.8067\ m}{s^2}\frac{1\ N \cdot s^2}{kg \cdot m} = 9.8067\ N$$

$$1\frac{kg_f}{cm^2} = 1\frac{kg_f}{cm^2}\frac{9.8067\ N}{kg_f}\left(\frac{100\ cm}{m}\right)^2\frac{Pa \cdot m^2}{1\ N} = 98067\ Pa$$

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Material Properties

- **Density**, ρ, is mass per unit volume
- Density is the reciprocal of specific volume, v ($\rho = 1/v$)
  - the specific volume, v, is used more commonly in thermodynamics
- The SI units for density are kg/m^3
- Engineering units for density are lb_m/ft^3
  - For water ρ is ~1000 kg/m^3 or 62.4 lb_m/ft^3; for air, ρ is ~1.2 kg/m^3 or 0.0765 lb_m/ft^3

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Ideal Gases

- From chemistry: PV = n$\mathscr{R}$T
  - n = m / M is the number of moles
    - for mass in kg n is in kilogram moles (kmol); for mass in lb_m, n is in pound moles (lbmol)
  - $\mathscr{R}$ = 8.31447 kJ/kmol·K = 10.7316 psia·ft^3 / lbmol·R is universal gas constant
  - R = $\mathscr{R}$/M is engineering gas constant that is different for each gas (For air R = 0.2870 kJ/kg·K = 0.3704 psia·ft^3/lbmol·K)
  - P = n$\mathscr{R}$T / V = (m/M)$\mathscr{R}$T / V = (m/V)($\mathscr{R}$/M)T
  - P = ρRT

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Material Properties II

- **Expansion coefficients**
  - Volume expansivity, β_P
  - Isothermal compressibility, κ_T
  - κ_T is always > 0; β_P may be either sign

$$\beta_P = \frac{1}{v}\left(\frac{\partial v}{\partial T}\right)_P = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_P \qquad \kappa_T = -\frac{1}{v}\left(\frac{\partial v}{\partial P}\right)_T = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial P}\right)_T$$

- **For Ideal gases**
  - Volume expansivity, β_P = 1 / T
  - Isothermal compressibility, κ_T = 1 / P

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Heat Capacity, c_p and c_v

- $dQ = c_x dT$ (c_x is heat capacity/specific heat)
  - Integrate for total heat transferred in constant x process from initial to final temperature
  - dimensions are energy/mass·temperature; can use °C or K (°F or R)
  - SI & engr units are J/kg·K & Btu/lb$_m$·R

• For all substances $c_P = c_v + \frac{T\beta_P^2}{\rho\kappa_T}$	• Liquids and solids: $c_P \approx c_v$; use c_p as common symbol

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Heat Transfer

Q is the total heat transfer with energy units of J or Btu

$\dot{Q}$ is the heat transfer rate in power units J/s = W or Btu/hr

Heat flux: $\dot{q} = \dot{Q}/A$

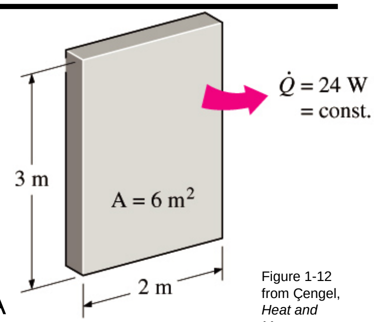

Figure 1-12 from Çengel, *Heat and Mass Transfer*

$$\dot{q} = \frac{\dot{Q}}{A} = \frac{24\text{ W}}{6\text{ m}^2} = 4\text{ W/m}^2$$

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Heat Transfer II

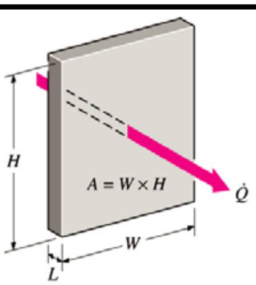

Figure from Çengel, *Heat and Mass Transfer*

FIGURE 1–24

In heat conduction analysis, *A* represents the area *normal* to the direction of heat transfer

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Fourier's Law

- Basic law for heat conduction
- Actually a vector equation $\dot{q}$ = –k grad T
- k is thermal conductivity
  - More on k on next slide
- For one dimensional heat transfer, $\dot{q}_x$ = –kdT/dx; integration (constant $\dot{q}_x$) gives

$$\dot{q} = \frac{k(T_1 - T_2)}{L} \quad or \quad \dot{Q} = \dot{q}A = \frac{kA(T_1 - T_2)}{L}$$

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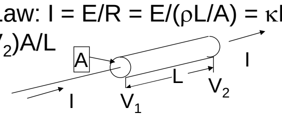
Thermal Conductivity I

- **Thermal conductivity**, k, a material property like electrical conductivity, κ
  - Ohm's Law: I = E/R = E/(ρL/A) = κEA/L = κ(V_1 – V_2)A/L



- SI units for κ are units for IL/(EA), which are amps·m/volts·m² = amps/volts·m
  - Units are (flow quantity) divided by (driving force times length)

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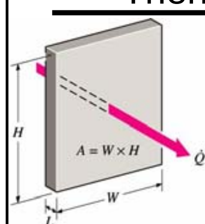
Thermal Conductivity II



- $\dot{Q}$ = heat flow rate in watts
- $T_1 – T_2$ = driving force in K
- A and L are cross sectional area and thickness
- Fourier Law: $\dot{Q}$ = kA/L(T_1 – T_2); k = thermal conductivity
- SI units for k are units of $\dot{Q}$L /ΔTA = watts.m/K·m² = watts/m·K
  - Engineering units: Btu/hr·ft·°F

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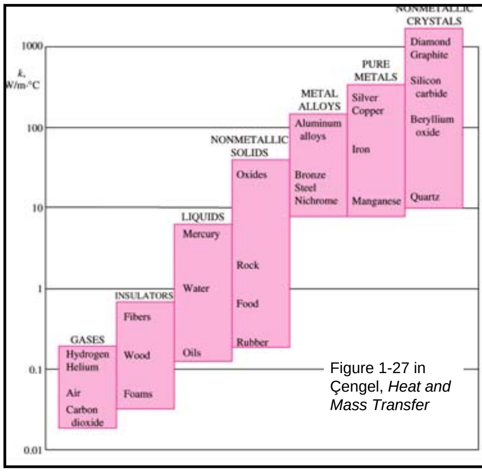
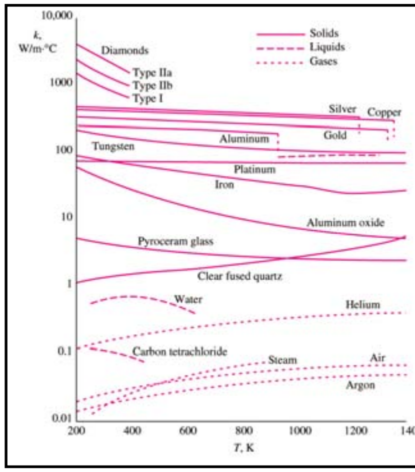


Figure 1-27 in Çengel, *Heat and Mass Transfer*

Thermal Conductivity Ranges over factor of 10^5 compared to range of 10^{32} for electrical conductivity



Temperature variation of thermal conductivity from Figure 1-29 in Çengel, *Heat and Mass Transfer*

Typical Units

Quantity	SI units	Engr units
Density	kg/m^3	lb_m/ft^3
Pressure & shear stress	1 kPa = 1 kN/m^2 = 1000 Pa	1 psi = 1 lb_f/in^2 = 144 psf = 144 lb_f/ft^2
Velocity	m/s	ft/s
Thermal conductivity	W/m·K = W/m·°C	Btu/hr·ft·R = Btu/hr·ft·°F
Heat capacity	J/kg·K = J/kg·°C	$Btu/lb_m \cdot R$ = $Btu/lb_m \cdot {}^oF$

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51

Conduction Problem

- Compute the heat flux through a solid that is 20 cm thick if the surface temperatures are at 100°C and 25°C if the solid is (a) aluminum or (b) pyroceram glass
  - What equation do we use? $\dot{q} = \frac{k(T_1 - T_2)}{L}$
  - What values do the variables in this equation have from the problem data?
    - L = 20 cm = 0.2 m, T_1 = 100°C, T_2 = 25°C
    - Find k values at average T = 62.5°C = 335.65 K

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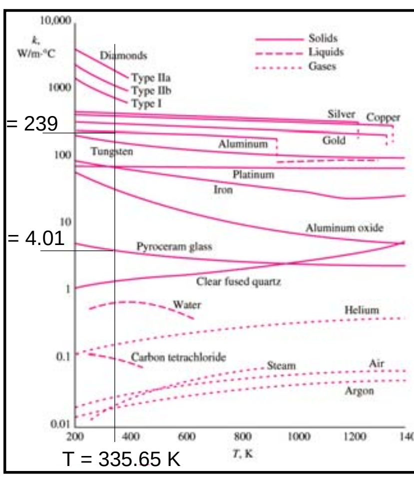
52



Required thermal conductivity values for problem found from interpolation in appendix tables A-3 and A-4; values shown here on Figure 1-29 in Çengel, *Heat and Mass Transfer*

53

Problem Results

- For aluminum, k = 239 W/m·K

$$\dot{q} = \frac{k(T_1 - T_2)}{L} = \frac{239\,W}{m \cdot K}\frac{(100-25)K}{0.2\,m}\frac{kW}{1000\,W} = \frac{89.6\,kW}{m^2 \cdot K}$$

- For pyroceram glass, k = 4.01 W/m·K

$$\dot{q} = \frac{k(T_1 - T_2)}{L} = \frac{4.01\,W}{m \cdot K}\frac{(100-25)K}{0.2\,m}\frac{kW}{1000\,W} = \frac{1.50\,kW}{m^2 \cdot K}$$

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54

Ohm's Law Analogy

- E = IR or I = E/R or flow equals driving force divided by resistance
- Fourier's law for one-dimensional conduction can be written in this form

$$\dot{Q} = \frac{kA(T_1 - T_2)}{L} \Rightarrow \dot{Q} = \frac{T_1 - T_2}{R} \Rightarrow R = \frac{L}{kA}$$

- Result for thermal resistance is similar to result for electrical resistance: R = L/κA, where κ = electrical conductivity

55

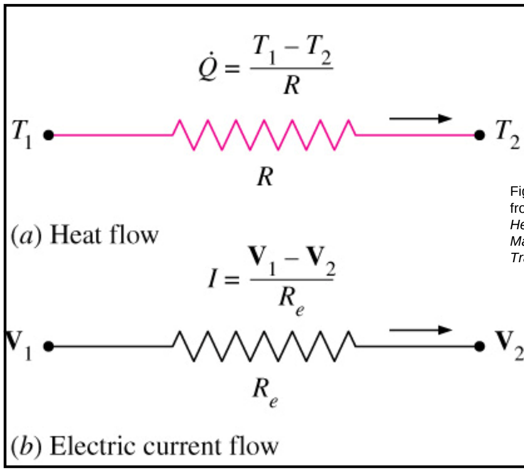


Figure 3-3 from Çengel, *Heat and Mass Transfer*

Convection Basics

This example is an external flow (flow over an object) with velocity relative to the object

The reference velocity, V_∞, and temperature T_∞ are called the free-stream values (far from the object)

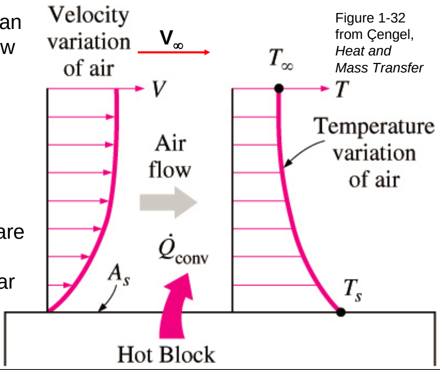


Figure 1-32 from Çengel, *Heat and Mass Transfer*

Convection Basics II

V∞ = reference velocity

T_∞ = reference temperature

A_s = surface area

T_s = surface temperature

V, T = variable velocity and temperature

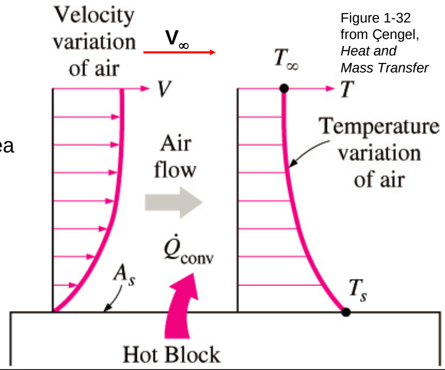


Figure 1-32 from Çengel, *Heat and Mass Transfer*

Convection Basics III

$$\dot{Q}_{conv} = hA_s(T_s - T_\infty)$$

h = heat transfer coefficient (W/m^2·K) or Btu/hr·ft^2·°F

h is found from empirical or theoretical equation

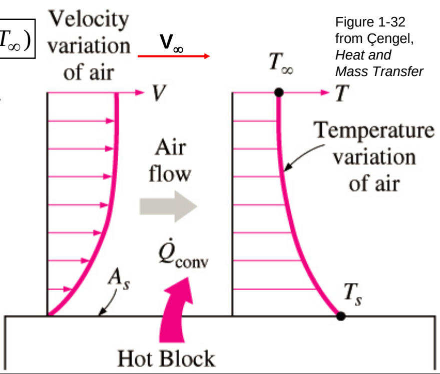


Figure 1-32 from Çengel, *Heat and Mass Transfer*

Basic Convection Equation

- $\dot{Q}_{conv} = hA_{surface}(T_{surface} - T_{fluid})$
- Algebraic heat transfer is from surface to fluid
  - Physical heat transfer is from fluid to surface if $\dot{Q}_{conv}$ is negative
- During first part of course we will be given h values
- Later we will learn how to find them from fluid and flow properties

60

Ohm's Law for Convection

- E = IR or I = E/R or flow equals driving force divided by resistance
- Convection heat transfer relation can be written in this form

$$\dot{Q} = hA\left(T_s - T_f\right) \quad \Rightarrow \quad \dot{Q} = \frac{T_s - T_f}{R} \quad \Rightarrow \quad R = \frac{1}{hA}$$

- No direct analogy between heat transfer coefficient and electrical properties as for thermal and electrical conductivity

Convection Equivalent Circuit

$$\dot{Q}_{conv} = hA_s(T_s - T_\infty)$$

Just as in an electrical circuit the direction of heat (current) flow is assumed in the equation; if the resulting heat (current) is negative the flow is in the opposite direction

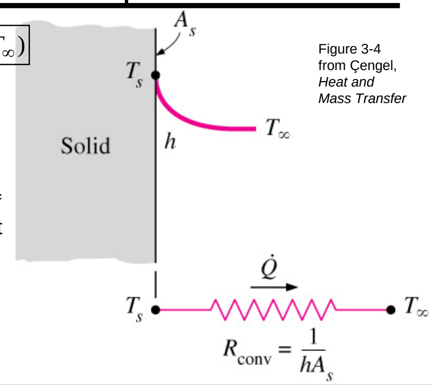
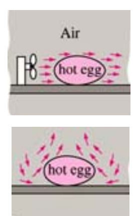


Figure 3-4 from Çengel, *Heat and Mass Transfer*

Convection Classifications

- **Free (natural) convection** comes from buoyancy, **forced convection** has a driven flow
- Flows contained in pipes and ducts are **internal flows**; egg pictures show **external flow**
- Other considerations are **laminar *vs.* turbulent** flow and convection during **boiling or condensation**



Eggs from Figure 1-33 in Çengel, *Heat and Mass Transfer*

Typical Convection Coefficients

Flow Description	W/m²·°C	Btu/hr·ft²·°F
Gas free convection	2 – 25	0.5 – 5
Liquid free convection	10 – 1000	2 - 175
Gas forced convection	25 – 250	5 – 45
Liquid forced convection	50 – 20,000	10 – 3,500
Boiling and Condensation	2,500 – 100,000	450 – 17,500

Convection Problem

- An electrical circuit board with a surface area of 100 cm² has to dissipate 10 W of heat that it produces. The temperature of the circuit board must be maintained at or below 70°C. Convection cooling in air with a heat transfer coefficient of 30 W/m²·K is used. What is the maximum air temperature that can be used for cooling?

Convection Problem II

- How do we analyze this problem?
- What is the equation that we use?

$$\dot{Q}_{conv} = hA_s(T_s - T_\infty)$$

- How do we match the data in this problem with the given equation
- First we have to say that the heat dissipated by the circuit is the convection heat transfer, $\dot{Q}_{conv}$

Convection Problem II

- An electrical circuit board with **surface area A_s = 100 cm²** has to dissipate $\dot{Q}_{conv}$ **= 10 W** of heat. The temperature of the circuit board **$T_s \le 70$°C**. Convection cooling in air with a heat transfer coefficient **h = 30 W/m²·K**. What is the maximum **air temperature, T_∞** that can be used for cooling?

$$\dot{Q}_{conv} = hA_s(T_s - T_\infty)$$

67

Convection Problem III

$$\dot{Q}_{conv} = hA_s(T_s - T_\infty) \quad \Rightarrow \quad T_s = \frac{\dot{Q}_{conv}}{hA_s} + T_\infty \le 70^oC$$

$$T_\infty \le 70^oC - \frac{\dot{Q}_{conv}}{hA_s} = 70^oC - \frac{10\,W\left(\frac{100\,cm}{m}\right)^2}{\frac{30\,W}{m^2\cdot{}^oC}(100\,cm^2)} = 37^oC$$

- Lower air temperatures will dissipate the same amount of heat while keeping a lower circuit board temperature

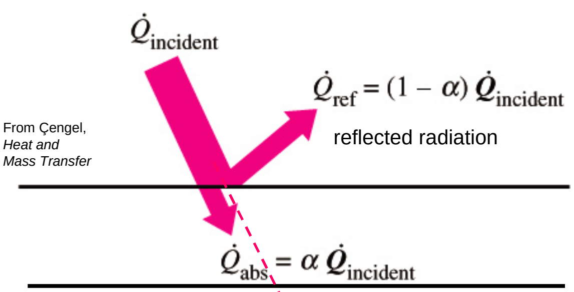
68

Radiation Heat Transfer

- All surfaces give off thermal radiation proportional to the fourth power of their temperature: $\dot{q}_{rad,emitted} = \varepsilon\sigma T^4$
  - ε is the emissivity ($0 \le \varepsilon \le 1$), a material property
    - ε = 1, perfect radiator, called "black body"
  - σ is the Stefan-Boltzmann constant = 5.670×10^{-8} W/m²·K⁴ = 0.1714×10^{-8} Btu/hr·ft²·R⁴
    - Must use absolute temperatures for radiation

69

From Çengel, *Heat and Mass Transfer*



For transparent solids some radiation is transmitted

FIGURE 1–36 The absorption of radiation incident on an opaque surface of absorptivity α.

70

Radiation Heat Transfer

- Complicated because of property dependence on wavelength of radiation and exchange among several surfaces
- Simplest case is two surfaces that form an enclosure. In this case the heat flux from surface 1 to surface 2 is based on a shape-emissivity factor, $\mathfrak{F}_{12}$

$$\dot{Q}_{rad,1\to2} = A_1\mathfrak{F}_{12}\sigma\left(T_1^4 - T_2^4\right)$$

71

Radiation Heat Transfer II

- Some simple cases of two surfaces

Small object (1) in large enclosure
$$\dot{Q}_{rad,1\to2} = A_1\varepsilon_1\sigma\left(T_1^4 - T_2^4\right)$$

Two infinite parallel planes
$$\dot{Q}_{rad,1\to2} = \frac{A_1\sigma\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

Two infinite concentric cylinders (1 is inner)
$$\dot{Q}_{rad,1\to2} = \frac{A_1\sigma\left(T_1^4 - T_2^4\right)}{\frac{1}{\varepsilon_1} + \frac{1-\varepsilon_2}{\varepsilon_2}\frac{r_1}{r_2}}$$

72

Ohm's Law for Radiation

- E = IR or I = E/R or flow equals driving force divided by resistance
- Radiation heat transfer relation can be rearranged to this form, but is nonlinear

$$\dot{Q}_{rad} = A_1\mathfrak{F}_{12}\sigma\left(T_1^4 - T_2^4\right) = A_1\mathfrak{F}_{12}\sigma\left(T_1 - T_2\right)\left(T_1^3 + T_2^3 + T_2^2T_1 + T_1^2T_2\right)$$

$$\dot{Q}_{rad} = \frac{T_1 - T_2}{\dfrac{1}{A_1\mathfrak{F}_{12}\sigma\left(T_1^3 + T_2^3 + T_2^2T_1 + T_1^2T_2\right)}} = \frac{T_1 - T_2}{R_{rad}}$$

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73

Ohm's Law for Radiation II

- Define radiation heat transfer coefficient analogous to that for convection where $R_{conv} = 1/Ah_{conv}$

$$R_{rad} = \frac{1}{A_1\mathfrak{F}_{12}\sigma\left(T_1^3 + T_2^3 + T_2^2T_1 + T_1^2T_2\right)} = \frac{1}{A_1h_{rad}}$$

- Use simple values for h_{rad} in initial parts of the course
  - Analyze more complex radiation analysis as final topic in course

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74

Radiation Heat Transfer Problem

- Compute the radiation flux a small surface with ε = 0.7 at 25°C in a large room whose surfaces are at 0°C

$$\dot{q}_{rad,1\to 2} = \frac{\dot{Q}_{rad,1\to 2}}{A_1} = \frac{A_1\varepsilon_1\sigma\left(T_1^4 - T_2^4\right)}{A_1} = \varepsilon_1\sigma\left(T_1^4 - T_2^4\right)$$

$$= (0.7)\left(\frac{5.670x10^{-8}\ W}{m^2 \cdot K^4}\right)\left[(298.15\ K)^4 - (273.15\ K)^4\right]$$

$$\dot{q}_{rad,1\to 2} = \frac{92.7\ W}{m^2}$$

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75

Radiation and Convection

- Can have radiation and convection in parallel: $\dot{Q}_{total} = \dot{Q}_{conv} + \dot{Q}_{rad}$
- Problem: what is total heat flux for the previous radiation problem if there is also convection with h = 20 W/m²·°C and T_∞ = 0°C

$$\dot{q}_{conv} = \frac{\dot{Q}_{conv}}{A} = h(T_s - T_\infty) = \frac{20\ W}{m^2 \cdot {}^oC}\left(25^oC - 0^oC\right) = \frac{500\ W}{m^2}$$

$$\dot{q}_{total} = \dot{q}_{conv} + \dot{q}_{rad} = \frac{500\ W}{m^2} + \frac{92.7\ W}{m^2} = \frac{593\ W}{m^2}$$

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76