111Equation Chapter 1 Section 1

1 INTRODUCTION TO HEAT TRANSFER

Cengel Chapter 1, or Welty *et al*. p 201-214 or Incropera *et al*. p 1-12

Learning objectives, *tasks*, readings, Learn ChemE Videos

1. Explain the differences between:
    a. Conduction
    b. Convection
    c. Radiation
    d. Driving forces, resistances, constants (k, h, σ)
2. Use the following equations to calculate heat transfer rates and explain the meanings of the terms in each equation:
    a. Fourier's Law (conduction)
    b. Newton's Law of Cooling (convection)
    c. Boltzman Equation (radiation)
    d. Learn ChemE – "Heat Transfer Basics"
    e. Multi-modal (Learn ChemE – "Potato Example")
3. *Begin filling in the table of symbols, definitions and units*

By the end of this week you should be able to:

- Determine which modes of heat transfer will be relevant for a given problem, and which are negligible
- Find, reference and use appropriate values of thermal conductivity and emissivity (along with other standard thermal properties of common fluids – e.g. density, heat capacity, etc)
- Set out a solution to a problem based on the method described (end of lecture notes), including diagrams, assumptions, data, analysis, calculations (with appropriate significant figures), and critical review of the answer

WHAT IS HEAT TRANSFER?

THERMODYNAMICS

- Energy (heat) can be transferred between system and surrounds.
- Heat goes from hot to cold regions.

Temperature difference = driving force

- Deals only with End states (eg at equilibrium).
- Tells nothing about modes or rates of Heat Transfer.

HEAT TRANSFER

- TIME TAKEN (s) TO TRANSFER THERMAL ENERGY (J)

RATE J/s = W

HEAT TRANSFER SYMBOLS AND UNITS

Actions for students:

- complete the units column in the table of symbols, and indicate which variables are vectors; and
- update table of symbols as course progresses.

TABLE OF HEAT TRANSFER SYMBOLS AND UNITS (note – textbooks vary widely!!!)

Symbol		Definition	Units
Study guide	Textbook (Incropera)		
q		heat transfer rate	W
A		heat transfer area	m^2
T		temperature	^{o}C or K or ^{o}F
R		resistance to heat transfer	
q”		heat transfer flux	W/m^2
Symbol		**Definition**	**Units**
Study guide	Textbook (Incropera)		
k		thermal conductivity	W/mK
h		heat transfer coefficient	W/m^2 K

σ		Stefan-Boltzmann constant, 5.669×10^{-8}	$W/m^2 K^4$
ε		Emissivity ($0 \le \varepsilon \le 1$) radiative property of a surface	

1.1 RATE EQUATIONS FOR PHYSICAL PROCESS

$$Rate = \frac{Driving\ Force}{Resistance}$$

EXAMPLES:

$q = \frac{\Delta T}{R}$ (W)

OHM'S LAW $I(C/s) = \frac{\Delta V}{R}$

ELECTRICAL CIRCUITS

MASS TRANSFER $\dot{m}$ (kg/s) = $\frac{\Delta C A}{R}$

1.2 THE GENERAL FORM OF HEAT TRANSFER EQUATIONS

The general form of the rate equation:

W $$q = \frac{A \Delta T}{R} \qquad \frac{m^2 \Delta K}{W} \qquad \frac{m^2 K}{}$$

Equation H-1

Where: q = heat transfer rate (W) J/s

A = heat transfer area (m^2) → AREA EXPOSED FOR HT

T = temperature (^oC or K) → K

R = resistance to heat transfer W/m^2K

Commonly expressed as heat flux:

$$\cancel{q} \, Q = \frac{q}{A} = f(\Delta T) \qquad \frac{W}{m^2}$$

Equation H-2

Where: q” = heat flux (W/m²)

Modes of heat transfer

Conduction: In a stationary medium, energy is transferred due to interactions between particles.

In gases: → ← - VERY FAR APART - FEW COLLISIONS

In liquids: → → ← - FAR APART - NOT MANY COLLISIONS

In solids: VERY CLOSE LOTS OF COLLISIONS ↳ HEAT TRANSFERS QUICKLY

IN GENERAL $q_{cond,S} > q_{cond,L} > q_{cond,G}$

Convection: Energy transfer between a surface and the adjacent fluid. Convection arises from the combined effects of *conduction* and *fluid flow*. CONVECTION ⟹ f(fluid properties, flow properties)

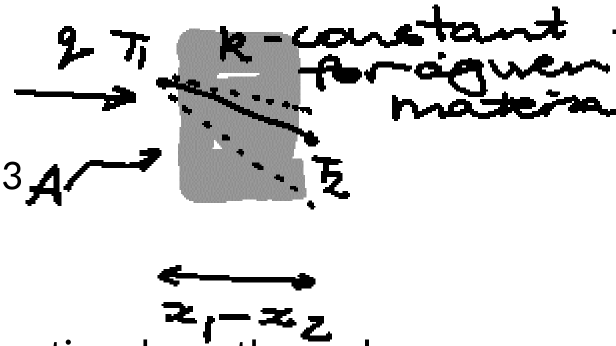
Radiation: Electromagnetic energy emitted at the molecular or atomic level, which transmits through space and is absorbed, transmitted or reflected by receiving molecules.

CONDUCTION

Rate of heat transfer: Fourier's Law

For 1-dimensional steady-state conduction, rate of heat transfer from T_2 to T_1:

Fourier's Law: $$q = -kA\frac{(T_1 - T_2)}{(x_1 - x_2)}$$ Equation H-3



Where:

- Negative sign: denotes heat flow in x direction down thermal gradient ($\frac{\Delta T}{\Delta x}$)
- k = thermal conductivity (W/mK)

Consider the rate equation for physical processes:

$$q = -\frac{\Delta T}{\Delta x} kA \qquad Rate = \frac{Driving\ Force}{Resistance} = \frac{\Delta T}{R}$$

For 1-d, steady state conduction, define in words, symbols and units:

Rate: q, rate of heat transfer, W

Driving force: ΔT, temperature difference in units of °C or °K

Resistance:

Δx Δx

RA for q (W) or $\frac{\;}{k}$ if q'' (W/m^2)

Which will have higher conductivity?

- Steel or brick? Steel ↑q because k↑
- Wood or rock? Rock ↑q " "
- Banana or air? Banana ↑q " "

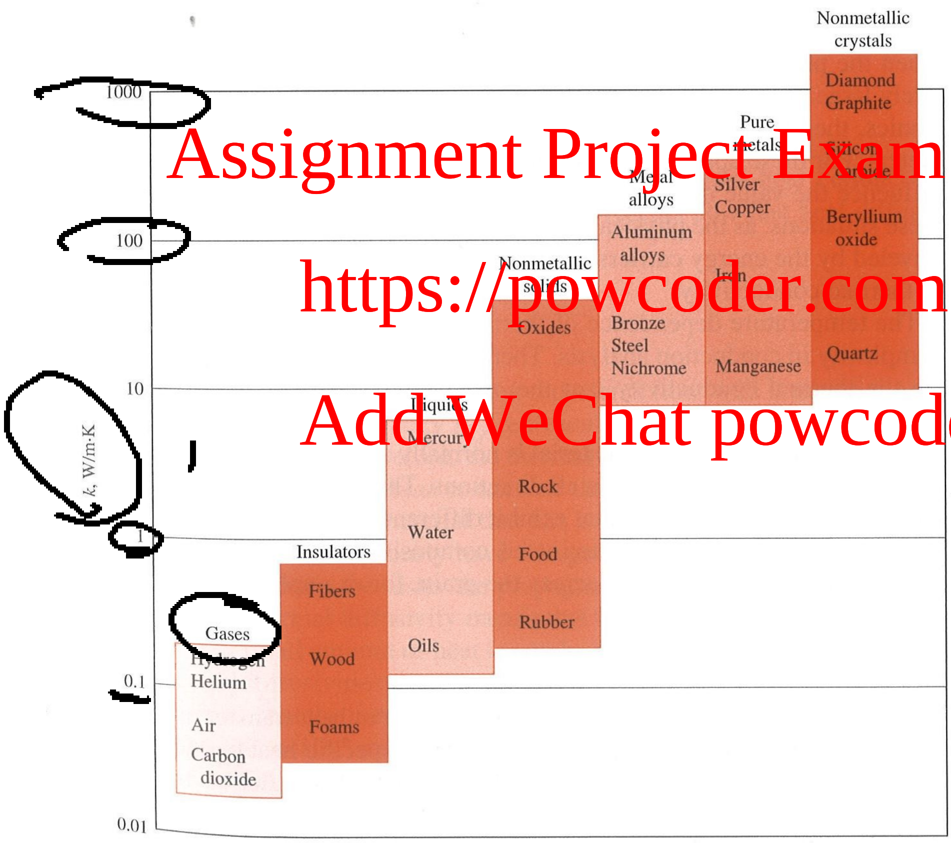
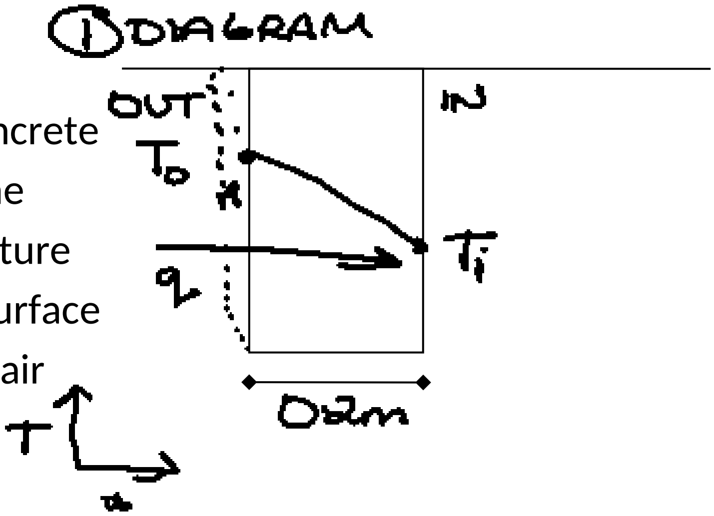


FIGURE 1–29
The range of thermal conductivity of various materials at room temperature.

1.3 EXAMPLE – WHAT IS THE RATE OF CONDUCTION THROUGH A CONCRETE WALL?

What is the rate of heat conducted through a concrete wall of width 20 cm, if the outside surface temperature is 35 °C, and the inside surface is kept at 22 °C, through air conditioning?

① DIAGRAM



② ASSUMPTIONS → EQUATION

- Steady state
- 1D conduction
- k is constant

③ FOURIER'S LAW $q = -kA\frac{\Delta T}{\Delta x}$

④ DATA $k_{concrete} = 1\ W/mK$

$$\frac{q}{m^2} = -\frac{1W}{mK} \times \frac{(T_o - T_i)K}{0.2m} \times \cancel{1m^2}$$

$$q'' = -\frac{1W}{mK} \times \frac{(35-20)K}{0.2}$$

$$= -65\frac{W}{m^2}$$

$\frac{65W}{m^2}$ from outside to inside

CONVECTION

Convection involves heat transferred from a surface to a fluid.

Examples: 

MECHANISM – COND + FLUID MOTION OR MOLECULES IN FLUID COLLIDING AND TRANSFERRING HEAT FROM THE SURFACE (HOT) TO THE COOLER FLUID.

Rate of heat transferred from surface at T_S to surrounding fluid, bulk temperature T_∞

NEWTON'S LAW OF COOLING

$$q = \underline{h}A\left(T_s - T_\infty\right)$$

Equation H-4

Where:

- h = heat transfer coefficient (W/m^2K) — CONVECTION f (Fluid props, Flow props, geo)
- T_S is the surface temperature, °C or K
- T_∞ is the bulk fluid temperature, °C or K

T_∞

T_{surr}

T_{fluid}

h is dependent on:

- Fluid velocity;
- System geometry,
- Nature of convection

- Fluid properties.

Values for h are usually derived from empirical dimensionless correlations. Week 5/6

Modes of Convection

1. <u>Forced Convection: fluid flow is driven by external force</u>

    - Gases: $h = 25 - 250\ Wm^{-2}K^{-1}$
    - Liquids: $h = 50 - 20{,}000\ Wm^{-2}K^{-1}$

fan
compressor
cyclone

e.g.

$h_{liquids} > h_{gases}$

HT more efficient at higher values of h ∴ usually higher for liquids

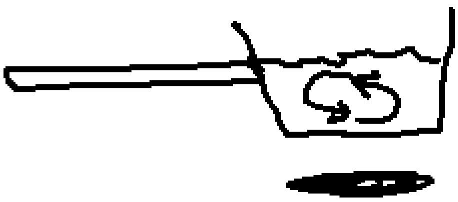
2. <u>Natural Convection:</u>

Flow induced by buoyancy forces due to temperature (or concentration) generated density differences.

- Gases: $h = 2 - 25\ Wm^{-2}K^{-1}$
- Liquids: $h = 50 - 1{,}000\ Wm^{-2}K^{-1}$

$h_n << h_F$

e.g. $h_L > h_G$



NO STRONG WIND
Occurs in the absence of external force.

heat plumes for equipment

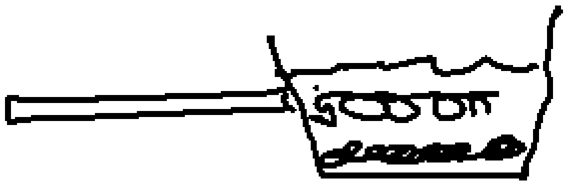
3. <u>Boiling & Condensation Convection:</u>

Phase change induced flow creates latent heat transfer and fluid mixing.

- Gases & Liquids: $h = 2{,}500 - 100{,}000\ Wm^{-2}K^{-1}$

e.g.

Efficient form of heat transfer!



BOILING

h values difficult to estimate ⇒ 3RD YEAR

RADIATION FROM SURFACE TO/FROM SURROUNDS

Examples:

Fire

Red hot heating element

metallic object left in the sun.

Solar panels - water heating or power generation

Rate of heat emitted from a surface at temperature T_S

$$q = A\varepsilon\sigma T_S^{\,4} \qquad \textit{Equation H-5}$$

$$q = A\varepsilon\sigma\left(T_S^{\,4} - T_{Surr}^{\,4}\right) \qquad \textit{Equation H-6}$$

Amt heat transferred from one object to surr.

sigma σ = Stefan-Boltzmann constant = 5.669 x 10^{-8} (W/m^2K^4)

T_S = absolute temperature (K) of emitting surface, T_{surr} = surrounds

ε = emissivity ($0 \le \varepsilon \le 1$) radiative property of a surface

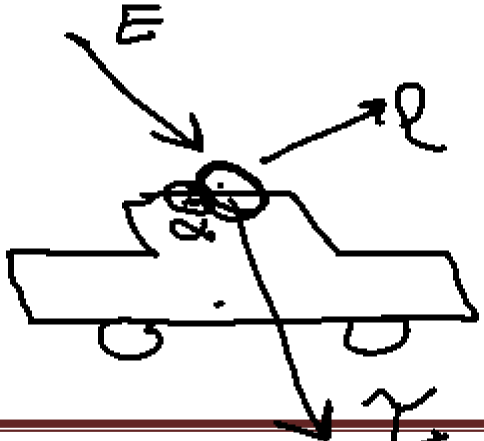
Constant

Foolproof ⇓ Use K

Radiation energy, E, striking a surface will be:

Blackbody $\varepsilon = 1$

- Absorbed, α, or
- Reflected, ρ, or
- Transmitted τ.



Energy Balance on the object.

That is,

$$\alpha + \rho + \tau = 1$$

Equation H-7

Absorptivity, α, Reflectivity, ρ , Transmissivity, τ and Emissivity, ε:

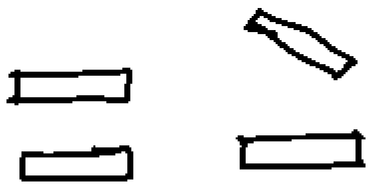
- Are optical properties; of an object
- Depend on MATERIAL and λ, WAVELENGTH OF LIGHT

Radiation differs from conduction and convection in that it

- Does not require the presence of matter — Radiation can occur in vacuum eg SOLAR RAD
- depends on T^4

Rate of heat transferred between (a) a body and surrounds, or (b) one body and another, due to radiation, depends on:

- Temp diff $(T_s^4 - T_{surr}^4)$
- areas
- Emissivities
- Geometry

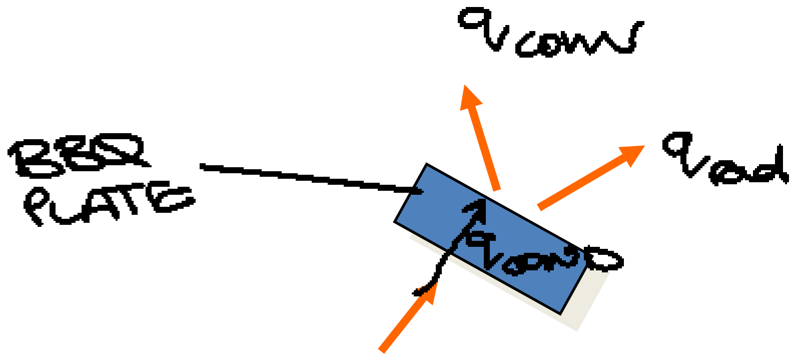


q_{cond}, q_{conv} q_{rad}
ALL TERMS IN AN EB.

COMBINED MODES

Many real situations involve heat transfer by more than 1 mode:

Solve by an energy balance using appropriate equations.



$E_{in} - E_{out} + \cancel{E_{st}} = 0$ for steady state (and LAW)

$q_{cond} - q_{conv} - q_{rad} = 0$

$$-kA\frac{(T_1 - T_2)}{\Delta x} - hA(T_s - T_\infty) - \varepsilon\sigma A(T_s^4 - T_{sur}^4) = 0$$

Q: How do know if rad + convection are both occurring in a problem?

A: They are both occurring <u>BUT</u>

Rad is only significant if very large temps (> 600 K) are involved because $\sigma \sim 10^{-8}$

1.4 SUMMARY: CONDUCTION, CONVECTION AND RADIATION

1-D STEADY STATE CONDUCTION IN A SOLID

Fourier's law

$q\,(W)$ $$q = -kA\frac{\Delta T}{\Delta x} = -kA\frac{(T_h - T_c)}{\Delta x} \qquad q''\left(\frac{W}{m^2}\right) = \frac{-k(T_h - T_c)}{\Delta x}$$

q = rate of heat conduction from $T_1 \rightarrow T_2$ (units: W)

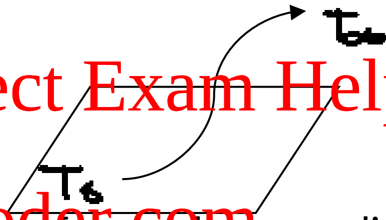
A = cross-sectional area (units: m^2) area exposed to heat transfer

k = thermal conductivity (units: W/mK) look this up in a table

CONVECTION FROM A SURFACE TO A FLUID

Newton's law

$$q = hA\left(T_S - T_\infty\right)$$



q = rate of heat transferred between surface and surrounding fluid (units: W) $q'' = q/A$ W/m^2

h = heat transfer coefficient (W/m^2K) can be looked up f(fluid + flow props + geo)

calc h in later weeks

T_S = surface temperature (units: °C or °K) ΔT in °C = °K

T_∞ = ambient fluid temperature (units: °C or °K)

RADIATION FROM A SURFACE TO SURROUNDS

$$q = \varepsilon\sigma\, AT_S^4$$ emitted by a surface

$$q = \varepsilon\sigma A(T_s^4 - T_{surr}^4)$$ exchange between surface + surrounds

ε = surface emissivity (units: —)

σ = Stefan-Bolzman constant = 5.67 x 10^{-8} $Wm^{-2}K^{-4}$

T_s = surface temperature (units: K) T_{surr} (K)

A = surface area (units: m^2)

CANNOT USE °C FOR RAD.

HOW TO SET OUT SOLUTIONS TO PROBLEMS: GUIDELINES/MARKING CRITERIA

Your solutions should to satisfy the following criteria:

1. **Diagram.** Draw a useful diagram of the physical system. Symbols, dimensions, materials, flows of energy and other relevant properties should be defined on the diagram.

   $q \rightarrow$ T, A, k, h

2. **Define the problem.** State what you will determine, e.g. heat loss from furnace to surrounding air.

   Steady state, 1D conduction

3. **Assumptions.** List and justify assumptions and simplifications.
4. **Data.** Clearly state data needed for calculations, including units and reference source

   k, ε etc ρ, Cp.

5. **Analysis.** Define appropriate equations, define all symbols.

What equations?

NO CALCS

6. **Calculation.** After completely developing the analysis in symbols, substitute numerical values and calculate results. Clearly show and explain working. Final answer should be stated clearly, with correct units and significant figures.

   PRACTICAL ANSWERS

7. **Interpretation**

   a. CHECK - how confident am I of the answer? e.g.

   Under what circumstances is it valid?

   Is the answer likely to be an under- or over-estimated?

   Can I check for sense against general knowledge, or knowledge of the problem?

   b. **ANALYSE** - what does it tell me about the system? e.g.

   What is controlling heat loss?

   c. APPLY - what actions should be taken because of what I learn from these calculations? e.g. How can heat loss be reduced?

The guidelines above will make it easier for you to solve new problems, and to check your work and correct errors.

Following the guidelines will also make it easier for others to understand your work, which is important for professional engineers. And the added bonus is that lecturers and tutors will find it easier to follow your work, and so better able to help you during the tutorial, and to award part marks during assessment when you have made an error.