Process Heat Transfer

Lec 1: Basic Concepts of Heat Transfer

Heat transfer and thermodynamics, Conduction heat transfer, Convective heat transfer, Radiative heat transfer.

Dr. Zayed Al-Hamamre

Content

- Thermodynamics and heat transfer
- Thermal energy, heat transfer and other forms of energy transfer,
- General energy balances and surface energy balances,
- The basic mechanisms of heat transfer, which are conduction, convection, and radiation, and Fourier's law of heat conduction, Newton's law of cooling, and the Stefan–Boltzmann law of radiation,
- The mechanisms of heat transfer that occur simultaneously in practice,
- Surface Energy Balance

Thermodynamics and Heat Transfer

- The science of thermodynamics deals with the amount of heat transfer as a system undergoes a process from one equilibrium state to another, and makes no reference to how long the process will take.

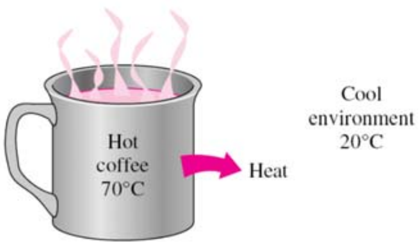
- The science of **heat transfer** deals with the determination of the rates of energy that can be transferred from one system to another as a result of temperature difference.

- **Thermodynamics** deals with equilibrium states and changes from one equilibrium state to another. **Heat transfer**, on the other hand, deals with systems that lack thermal equilibrium, and thus it is a nonequilibrium phenomenon.

Heat Transfer

- The basic requirement for heat transfer is the presence of a temperature difference.

- The second law requires that heat be transferred in the direction of decreasing temperature.



  - The temperature difference is the driving force for heat transfer.

  - The rate of heat transfer in a certain direction depends on the magnitude of the temperature gradient in that direction.

  - The larger the temperature gradient, the higher the rate of heat transfer.

Objectives of Heat Transfer Science

- To extend thermodynamics analysis through the study of the ***modes*** of heat transfer.
- Development of relations to calculate heat transfer ***rates***.

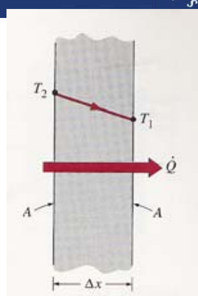
What is heat transfer?

Heat transfer is energy in transit due to a temperature difference.

How is heat transferred?

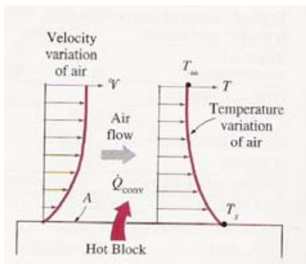
Heat is transferred through three modes: Conduction, Convection and Radiation

Modes of Heat Transfer



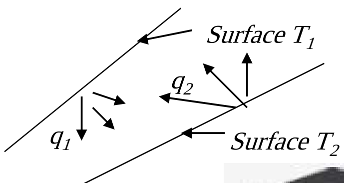
- **Conduction: Transmission of heat through a substance without perceptible motion of the substance.**

  ⇒ Metals: flow of free electron
  ⇒ Crystals: lattice vibrations
  ⇒ Fluids: molecular collisions (kinetic theory of gases)



- **Convection: refers to heat transfer which occurs between a surface and a moving fluid when they are at different temperatures .**

  ⇒ Convection associated with a change of phase: boiling, evaporation, condensation – these processes are often regarded as distinct heat transfer processes



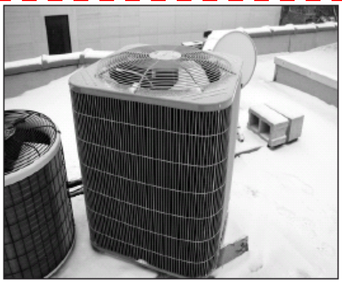
- **Thermal radiation**

  ⇒ Photons, which travels almost unimpeded through air from one surface to another

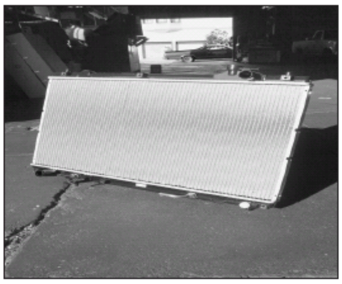
Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Application Areas of Heat Transfer


The human body


Air conditioning systems


Airplanes


Car radiators


Power plants


Refrigeration systems

Heat and Other Forms of Energy

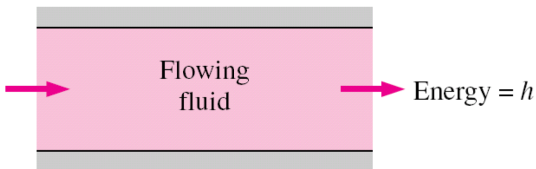
- Energy can exist in numerous forms such as:
  - thermal,
  - mechanical,
  - kinetic,
  - potential,
  - electrical,
  - magnetic,
  - chemical, and
  - nuclear.
- Their sum constitutes the **total energy** *E* (or *e* on a unit mass basis) of a system.
- The sum of all microscopic forms of energy is called the **internal energy** of a system.

Heat and Other Forms of Energy

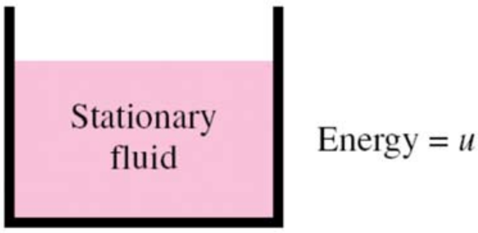
- **Internal energy** may be viewed as the sum of the kinetic and potential energies of the molecules.
- The kinetic energy of the molecules is called **sensible heat**.
- The internal energy associated with the phase of a system is called **latent heat**.
- The internal energy associated with the atomic bonds in a molecule is called **chemical** (or **bond**) **energy**.
- The internal energy associated with the bonds within the nucleus of the atom itself is called **nuclear energy**.

Internal Energy and Enthalpy

- In the analysis of systems that involve fluid flow, we frequently encounter the combination of properties u and $P\upsilon$.



- The combination is defined as **enthalpy** ($h=u+P\upsilon$).
- The term $P\upsilon$ represents the flow energy of the fluid (also called the flow work).



Specific Heats of Gases, Liquids, and Solids

- **Specific heat** is defined as *the energy required to raise the temperature of a unit mass of a substance by one degree.*

- Two kinds of specific heats:
  - specific heat at constant volume c_v, and
  - specific heat at constant pressure c_p.

- The specific heats of a substance, in general, depend on two independent properties such as temperature and pressure.

- For an *ideal gas*, however, they depend on *temperature* only.

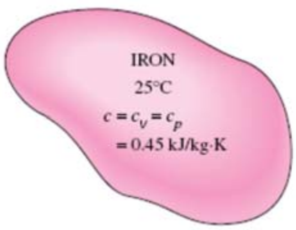
Specific Heats

- At low pressures all real gases approach ideal gas behavior, and therefore their specific heats depend on temperature only.

- A substance whose specific volume (or density) does not change with temperature or pressure is called an **incompressible substance**.

- The constant-volume and constant-pressure specific heats are identical for incompressible substances.

- The specific heats of incompressible substances depend on temperature only.



Energy Transfer

- Energy can be transferred to or from a given mass by two mechanisms:
  - heat transfer, and
  - work.

- The amount of heat transferred during a process is denoted by Q.

- The amount of heat transferred per unit time is called **heat transfer rate**, and is denoted by $\dot{Q}$.

- The total amount of heat transfer Q during a time interval Δt can be determined from

$$Q = \int_0^{\Delta t} \dot{Q}\,dt \qquad \text{(J)}$$

- The rate of heat transfer per unit area normal to the direction of heat transfer is called **heat flux**, and the average heat flux is expressed as

$$\dot{q} = \frac{\dot{Q}}{A} \qquad (\text{W/m}^2)$$

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

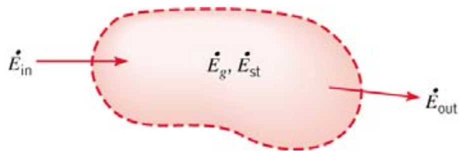
The First Law of Thermodynamics

- The **first law of thermodynamics** states that *energy can neither be created nor destroyed during a process; it can only change forms.*

(Total energy entering the system) - (Total energy leaving the system) = (Change in the total energy of the system)

The **energy balance** for any system undergoing any process can be expressed as (in the rate form)

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal kinetic, potential, etc., energies}} \quad \text{(W)}$$



Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

- In heat transfer problems it is convenient to write a **heat balance** and to treat the conversion of nuclear, chemical, mechanical, and electrical energies into thermal energy as *heat generation.*

- The *energy balance* in that case can be expressed as

$$\underbrace{Q_{in} - Q_{out}}_{\text{Net heat transfer}} + \underbrace{E_{gen}}_{\text{Heat generation}} = \underbrace{\Delta E_{thermal,system}}_{\text{Change in thermal energy of the system}} \quad \text{(J)}$$

Energy Balance

Closed systems

Stationary closed system, no work:

$$Q = mc_v\Delta T \quad \text{(J)}$$

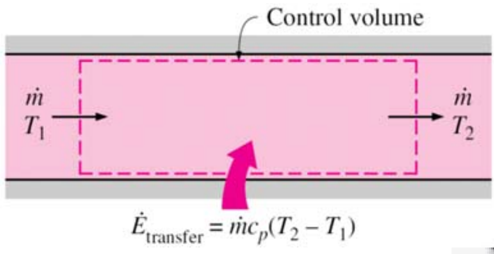
Steady-Flow Systems

For system with one inlet and one exit:

$$\dot{m}_{in} = \dot{m}_{out} = \dot{m} \quad \text{(kg/s)}$$

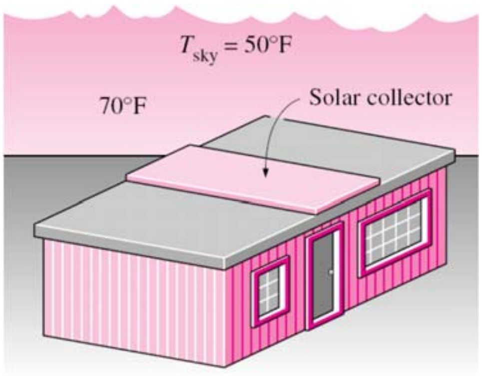
When kinetic and potential energies are negligible, and there is no work interaction

$$\dot{Q} = \dot{m}\Delta h = \dot{m}c_p\Delta T \quad \text{(kJ/s)}$$



Heat Transfer Mechanisms

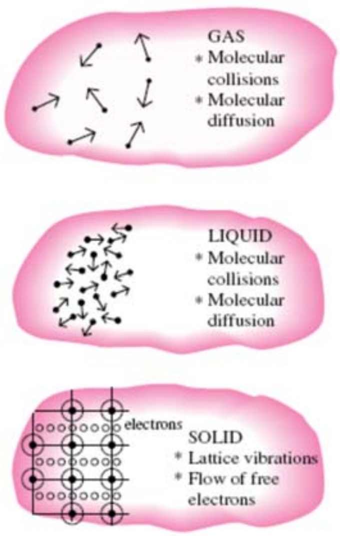
- Heat can be transferred in three basic modes:
  - conduction,
  - convection,
  - radiation.



- All modes of heat transfer require the existence of a temperature difference.
- All modes are from the high-temperature medium to a lower-temperature one.

Conduction

- Conduction is the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as a result of interactions between the particles.
- Conduction can take place in solids, liquids, or gases
  - In gases and liquids conduction is due to the collisions and diffusion of the molecules during their random motion.
  - In **solids** conduction is due to the combination of vibrations of the molecules in a lattice and the energy transport by free electrons.



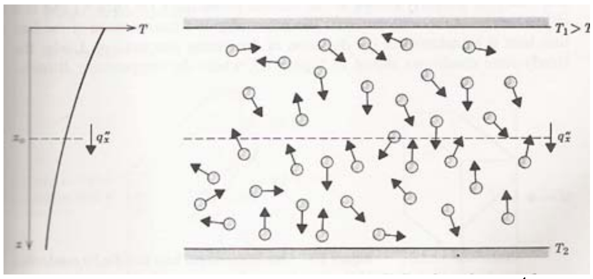
Conduction

Physical mechanism: based on atomic and molecular activity

⇒ Conduction can be viewed as transfer of energy from the more energetic to less energetic particles of a substance due to interaction between particles (kinetic energy)

Consider a gas occupy the two surfaces shown in the drawing with no bulk motion at any point:

Energy $\propto$ *T*



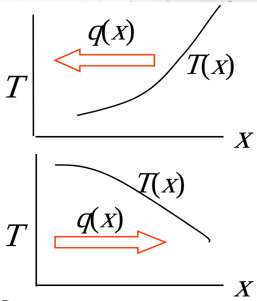
$\therefore \uparrow T$ ⇒ Kinetic energy ⇒ Molecular energy

⇒ ↑ collisions of neighbouring molecules

⇒ Transfer of energy from more energetic to less energetic

energy is related to the random translation of motion of internal energy + vibrational motion of the molecules

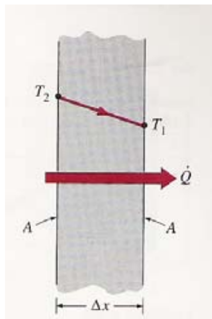
⇒ Thus, energy transfers in the direction of decreasing temperature



Rate equation for quantification of conduction – Fourier's law

Assumptions: 1. Homogeneous medium

2. One-dimensional heat flow (what does it mean?)



➢ Consider steady heat conduction through a large plate wall of thickness $\Delta x = L$ and surface area A.

➢ *Experimentally, it was shown that the rate of heat transfer, q, through the wall is doubled when ΔT across the wall or A normal to the direction of heat transfer is doubled, but halved when the wall thickness L is doubled. That is:*

Rate of heat conduction $\propto$ (Area) (Temperature difference)/(Thickness)

Or,

$$\dot{Q} = kA\frac{\Delta T}{\Delta x}$$

Where k, thermal conductivity of the material, a measure of the ability of a material to conduct heat

In the limiting case of $\Delta x \to 0$, the above equation reduces to the differential form:

$$\dot{Q} = -kA\frac{dT}{dx}$$

← **Fourier's law of heat conduction**

Remarks

⇒ Area (A) is perpendicular to the vector of heat flow; thickness (L) is parallel to the vector of heat flow.

⇒ First step in heat conduction problem: **evaluate A and L properly.**

⇒ In this course, we will use exclusively SI unit:

$\dot{Q}$ [W (J/s)] Or flux, $\dot{Q}/A$ [W/m²]; A [m²]; T [K]; L [m] ⇒ k [W/m K]

⇒ **Negative sign** is the sequence of fact that heat is transferred in the direction of decreasing temperature, i.e. $q(x)$ and $T(x)$ are opposite.

If k is constant and steady state exists, integration of Fourier's equation from T_1 to T_2 gives:

$$\dot{Q} = -kA\frac{T_2 - T_1}{L}$$

Or,

$$\dot{Q}/A = \frac{T_1 - T_2}{L/k}$$

⇒ Analogy with Ohms law ($I = V/R$):

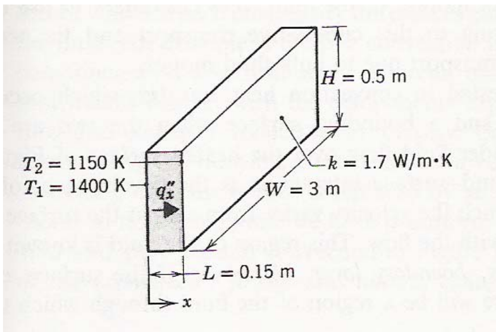
Driving force = $T_1 - T_2$ (corresponds to V)

Thermal Resistance = L/k (corresponds to R)

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Example:

The wall of an industrial furnace is constructed from 0.15 m thick fireclay brick having a thermal conductivity of 1.7 W/m.K. Measurements made during steady state operation reveal temperatures of 1400 and 1150 K at the inner and outer surfaces, respectively. What is the rate of heat loss through a wall which is 0.5 m by 3 m on a side?

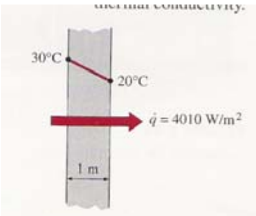


Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

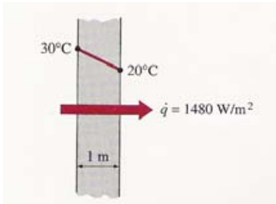
Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Thermal conductivity - k

⇒ It is a property of materials, which is a measure of the ability of the material to conduct heat



(a) Copper (k = 401 W/m·°C)



(b) Silicon (k = 148 W/m·°C)

⇒ k depends on microscopic structure of the substance;

Generally: $k_{solids} > k_{liq} > k_{gas}$ **Why??**

Table 1-1 | Thermal conductivity of various materials at 0°C.

Material	Thermal conductivity k, W/m·°C	Thermal conductivity k, Btu/h·ft·°F
Metals:		
Silver (pure)	410	237
Copper (pure)	385	223
Aluminum (pure)	202	117
Nickel (pure)	93	54
Iron (pure)	73	42
Carbon steel, 1% C	43	25
Lead (pure)	35	20.3
Chrome-nickel steel (18% Cr, 8% Ni)	16.3	9.4
Nonmetallic solids:		
Diamond	2300	1329
Quartz, parallel to axis	41.6	24
Magnesite	4.15	2.4
Marble	2.08–2.94	1.2–1.7
Sandstone	1.83	1.06
Glass, window	0.78	0.45
Maple or oak	0.17	0.096
Hard rubber	0.15	0.087
Polyvinyl chloride	0.09	0.052
Styrofoam	0.033	0.019
Sawdust	0.059	0.034
Glass wool	0.038	0.022
Ice	2.22	1.28
Liquids:		
Mercury	8.21	4.74
Water	0.556	0.327
Ammonia	0.540	0.312
Lubricating oil, SAE 50	0.147	0.085
Freon 12, CCl_2F_2	0.073	0.042
Gases:		
Hydrogen	0.175	0.101
Helium	0.141	0.081
Air	0.024	0.0139
Water vapor (saturated)	0.0206	0.0119
Carbon dioxide	0.0146	0.00844

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Thermal Conductivity

- The thermal conductivity of a material is a measure of the ability of the material to conduct heat.

- High value for thermal conductivity

  → good heat conductor

- Low value

  → poor heat conductor or *insulator.*

Effect of temperature of *k*:

- As previously mentioned, conduction depends merely on the molecular motion:

$$\uparrow T \Rightarrow \uparrow \text{energy} \Rightarrow \text{faster transport of energy}$$

$$\therefore k = f(T)$$

$\Rightarrow$ Based on kinetic theory for gases:

$$k \propto \sqrt{T}$$

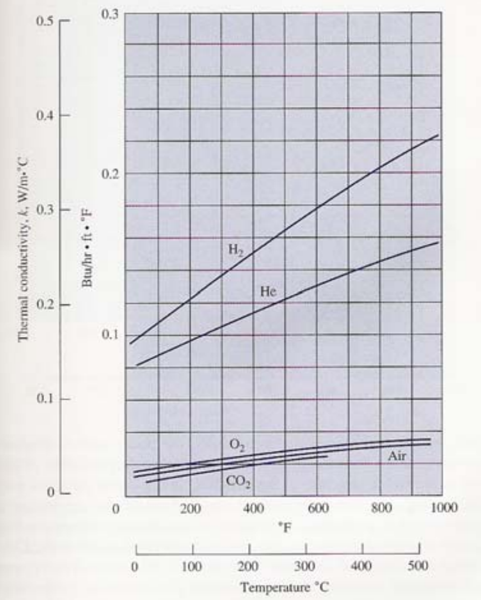
For most gases, at low to modertae *P*;

$$k = f(T) \text{ only}$$

At high *P*, close to critical pressure:

$$k = f(T, P) \text{ is needed}$$

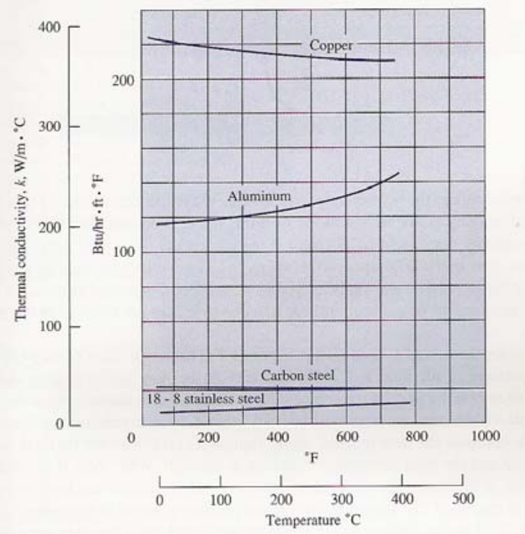
Figure 1-4 | Thermal conductivities of some typical gases [1 W/m · °C = 0.5779 Btu/h · ft · °F].



Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Effect of temperature of *k*:

Figure 1-6 | Thermal conductivities of some typical solids.



- For **liquids:** the mechanism of thermal energy conduction is similar to that of gases. However, situation is more complex since molecules are more closely spaced and molecular force fields exert a strong influence on the energy exchange in the collision process

$\Rightarrow$ *k* less dependent than gases

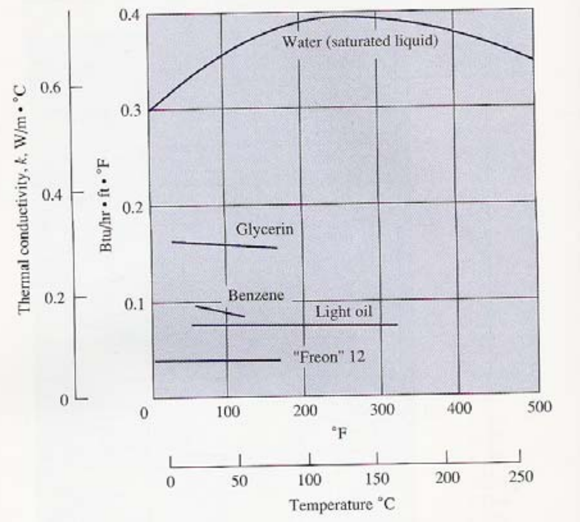
Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Effect of temperature of *k*:

- For **solids:** two modes for thermal conduction:

1. Lattice vibration
2. Transport by free electrons (*electron gas*)

Figure 1-5 | Thermal conductivities of some typical liquids.



Thermal insulators:

- Materials of low *k* values can thus be used as insulators

⇒ At high temperatures, energy transfer through insulating materials may involve several modes:

1. Conduction through the fibrous or porous solid material
2. Conduction through the air trapped in the void spaces, and
3. Radiation at relatively high temperature

Table 1-2 | Effective thermal conductivities of cryogenic insulating materials for use in range 15°C to –195°C. Density range 30 to 80 kg/m^3.

Type of insulation	Effective *k*, mW/m·°C
1. Foams, powders, and fibers, unevacuated	7–36
2. Powders, evacuated	0.9–6
3. Glass fibers, evacuated	0.6–3
4. Opacified powders, evacuated	0.3–1
5. Multilayer insulations, evacuated	0.015–0.06

- ***Super-insulators:*** special insulating materials used for storage and transport of cryogenic liquids, e.g. liquid H_2.

⇒ act at very low temperatures, about -250^{o}C

⇒ Normally consist of multilayers of highly reflective materials separating by insulating space.

Thermal diffusivity

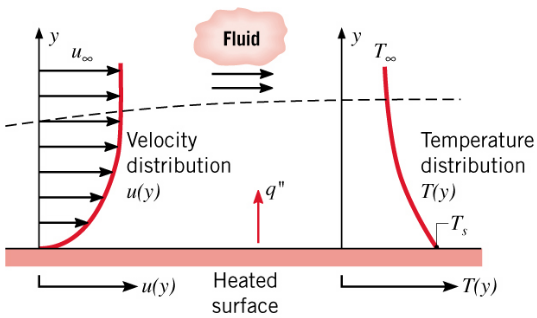
$$\alpha = \frac{\text{Heat conducted}}{\text{Heat stored}} = \frac{k}{\rho c_p} \qquad (\mathrm{m^2/s})$$

- The **thermal diffusivity** represents how fast heat diffuses through a material.
- Appears in the transient heat conduction analysis.
- A material that has a high thermal conductivity or a low heat capacity will have a large thermal diffusivity.
- The larger the thermal diffusivity, the faster the propagation of heat into the medium.

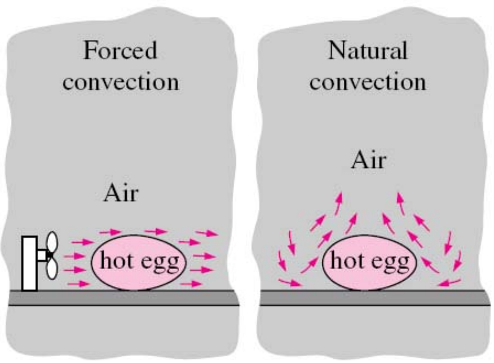
Convection

Convection = Conduction + Advection

(fluid motion)



- Convection is the mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion.
- Convection is commonly classified into three sub-modes:
  - Forced convection,
  - Natural (or free) convection,
  - Change of phase (liquid/vapor, solid/liquid, etc.)



Convection

- The rate of *convection heat transfer* is expressed by **Newton's law of cooling** as

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

h is the *convection heat transfer coefficient* in **W/m²°C**.

- *h* depends on variables such as:
  - the surface geometry,
  - the nature of fluid motion,
  - the properties of the fluid,
  - the bulk fluid velocity.

TABLE 1–5

Typical values of convection heat transfer coefficient

Type of convection	h, W/m² · °C*
Free convection of gases	2–25
Free convection of liquids	10–1000
Forced convection of gases	25–250
Forced convection of liquids	50–20,000
Boiling and condensation	2500–100,000

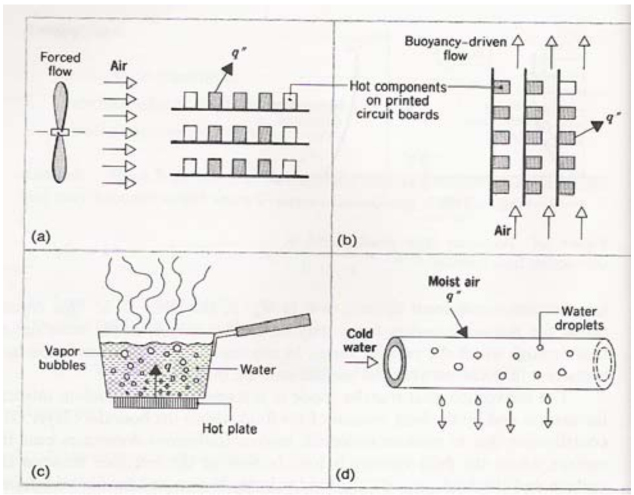
*Multiply by 0.176 to convert to Btu/h · ft² · °F.

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Natural and Forced Convection:

➢ The forces used to create convection currents in fluids are of two types:

❑ *Natural convection*: if the hot plate exposed to ambient air without external sources of motion, i.e. the movement of air is due to density gradient near the plate (i.e. difference in density causes the ΔT in the fluid).



❑ *Forced convection*: If the currents are set in motion by action of a mechanical device, such as a pump or agitator blower. The flow is independent of the density.

❑ *Boiling* and *Condensation*: grouped as convection.

⇒ energy is convected by latent heat exchange or phase transition

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Generally,

$h_{free} < h_{forced} < h_{boiling}$ & $h_{condensation}$

Example: Water at 300 K flows over both sides of a plate of 1 m × 2 m in area, maintained at 400 K. If the convective heat transfer coefficient is 200 W/m2.K, calculate the heat transfer.

$$\dot{Q} = 2hA(T_s - T_\infty)$$ **Why 2?**

$$\therefore Q = (2)\ (200)\ (1)\ (2)\ (400 - 300)$$

$$Q = 80{,}000 \text{ W}$$

Approximate values of convection heat-transfer coefficients

Mode	h, W/m² · °C	h, Btu/h · ft² · °F
Free convection, ΔT = 30°C		
Vertical plate 0.3 m [1 ft] high in air	4.5	0.79
Horizontal cylinder, 5-cm diameter, in air	6.5	1.14
Horizontal cylinder, 2-cm diameter, in water	890	157
Heat transfer across 1.5-cm vertical air gap with ΔT = 60°C	2.64	0.46
Forced convection		
Airflow at 2 m/s over 0.2-m square plate	12	2.1
Airflow at 35 m/s over 0.75-m square plate	75	13.2
Air at 2 atm flowing in 2.5-cm-diameter tube at 10 m/s	65	11.4
Water at 0.5 kg/s flowing in 2.5-cm-diameter tube	3500	616
Airflow *across* 5-cm-diameter cylinder with velocity of 50 m/s	180	32
Boiling water		
In a pool or container	2500–35,000	440–6200
Flowing in a tube	5000–100,000	880–17,600
Condensation of water vapor, 1 atm		
Vertical surfaces	4000–11,300	700–2000
Outside horizontal tubes	9500–25,000	1700–4400

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Radiation Heat Transfer

- Radiation is the energy emitted by matter in the form of *electromagnetic waves* as a result of the changes in the electronic configurations of the atoms or molecules.
- In heat transfer studies we are interested in *thermal radiation* (radiation emitted by bodies because of their temperature).
- Although we will focus on radiation from solid surfaces, emissions may also occur from liquids and gases.
- Heat transfer by radiation does not require the presence of an *intervening medium.*
- Heat transfer through a vacuum is by radiation only since conduction or convection requires the presence of a material medium.

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Radiation - Emission

- The maximum rate of radiation that can be emitted from a surface at a thermodynamic temperature T_s (in K or R) is given by the Stefan–Boltzmann law as

$$\dot{Q}_{emit,\max} = \sigma A_s T_s^4 \qquad (W)$$

s =5.670X10^8 W/m^2·K^4 is the *Stefan–Boltzmann constant.*

- The **idealized surface** that emits radiation at this **maximum rate** is called a **blackbody.**

- The radiation emitted by all real surfaces is less than the radiation emitted by a blackbody at the same temperature, and is expressed as

$$\dot{Q}_{emit,\max} = \varepsilon\sigma A_s T_s^4 \qquad (W)$$

$$0 \le \varepsilon \le 1$$

- ε is the **emissivity** of the surface (Table 1-6)

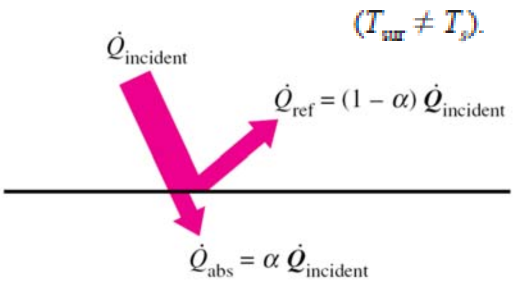
Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Radiation - Absorption

- Heat transfer at a gas/surface interface involves radiation emission from the surface and may also involve the absorption of radiation incident from the surroundings (irradiation, $Q_{incident}$), as well as convection.

- The rate at which a surface absorbs radiation is:

$$\dot{Q}_{absorbed} = \alpha \dot{Q}_{incident}$$



$\dot{Q}_{incident}$: The rate at which radiation is incident on the surface $= \sigma A_s T_{surr}^4, \quad (W)$

α : The absorptivity of the surface $\quad 0 \le \alpha \le 1$

$\longrightarrow \quad \dot{Q}_{absorbed} = \alpha\sigma A_s T_{surr}^4, \quad (W)$

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Radiation - Absorption

- Both ε and α depend on the temperature and the wavelength of the radiation.
- Kirchhoff's law of radiation: the emissivity and the absorptivity of a surface at a given temperature and wavelength are equal

$$\varepsilon = \alpha$$

- When a surface of emissivity ε and surface area A_s at temperature T_s is completely enclosed by a much larger (or black) surface at T_{surr} separated by a gas that does not intervene with radiation, *the net radiation heat rate between these two surfaces is given by*

Radiation - Absorption

$$\dot{Q}_{rad} = \dot{Q}_{emitted} - \dot{Q}_{absorbed}$$
$$= \epsilon\sigma A_s T_s^4 - \alpha\sigma A_s T_{surr}^4$$

But ε = α:

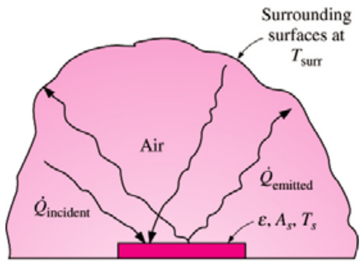
- The net radiation heat flux from the surface due to exchange with the surrounding is

$$\longrightarrow \quad \dot{Q}_{rad} = \epsilon\sigma A_s(T_s^4 - T_{surr}^4) \qquad ,(W)$$

or $$\dot{Q}_{rad} = h_r A_s(T_s - T_{surr})$$

h_r: radiation heat transfer coefficient (W/m^2.K)

$$\longrightarrow \quad h_r = \epsilon\sigma(T_s + T_{surr})(T_s^2 + T_{surr}^2)$$



$\dot{Q}_{rad} = \varepsilon\sigma A_s(T_s^4 - T_{surr}^4)$

FIGURE 1–37
Radiation heat transfer between a surface and the surfaces surrounding it.

Radiation - Absorption

For combined convection and radiation:

$$\dot{Q} = \dot{Q}_{conv} + \dot{Q}_{rad}$$

$$= hA_s(T_s - T_\infty) + h_r A_s(T_s - T_{surr})$$

If :

$$T_{surr} = T_\infty$$

Then $$\dot{Q} = h_{combined} A_s(T_s - T_\infty)$$

$h_{combined}$: combined heat transfer coefficient

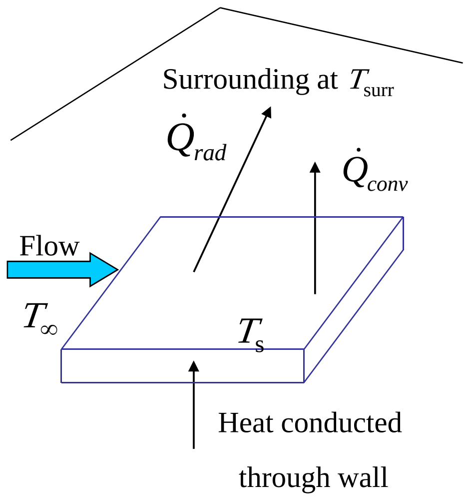
- It is possible that all three modes of heat transfer are present; in this case heat conducted through the wall is removed from the plate surface by a combination of convection and radiation.

Energy balance gives:

$$\dot{Q}_{cond} = \dot{Q}_{conv} + \dot{Q}_{rad}$$

Or,

$$-kA\left.\frac{dT}{dy}\right|_{y=0} = hA(T_s - T_\infty) + \varepsilon\sigma A(T_s^4 - T_{surr}^4)$$



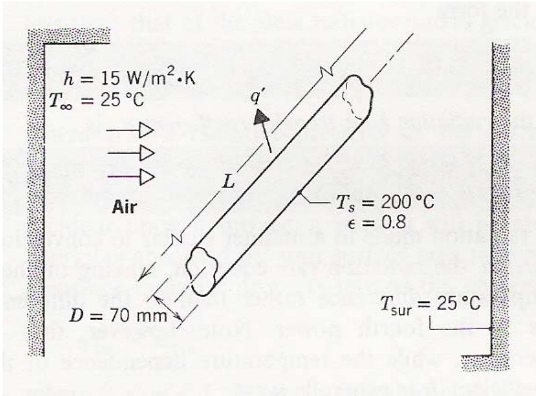
Example

An insulated steam pipe passes through a room in which the air and walls are at 25°C. The outside diameter of the pipe is 70 mm, and its surface temperature and emmisivity are 200°C and 0.8, respectively. If the coefficient associated with free convection heat transfer from the surface to the air is 15 W/m^2.K, what is the rate of heat loss from the surface per unit length of pipe?

Assumptions:

1. Steady state conduction exist
2. Radiation exchange between the pipe and the room is between a small surface enclosed within a much larger surface

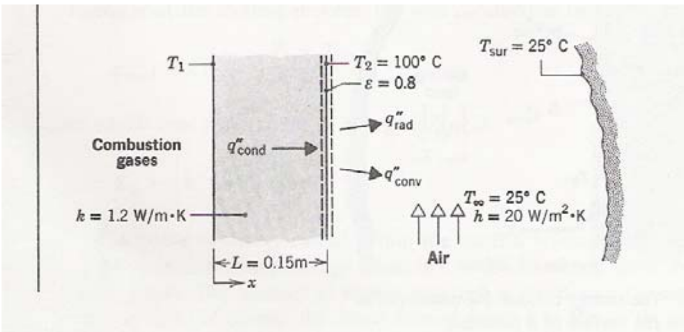
Schematic



Example Cont.

Example

The hot combustion gases of a furnace are separated from the ambient air and its surrounding, which are at 25°C, by a brick wall 0.15 m thick. The brick has a thermal conductivity of 1.2 W/m.K and a thermal emissivity of 0.8. Under steady-state conditions and out surface temperature of 100°C is measured. Free convection heat transfer to the air adjoining this surface is characterized by a convection coefficient h = 20 W/m^2.K. What is the brick inner surface temperature?



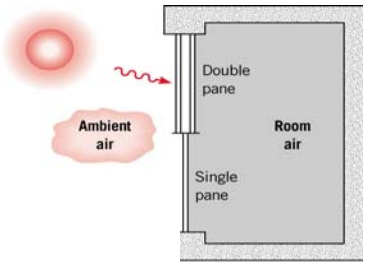
Answer: $T_1 = 352°C$

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Example

Process identification for single-and double-pane windows

Schematic:



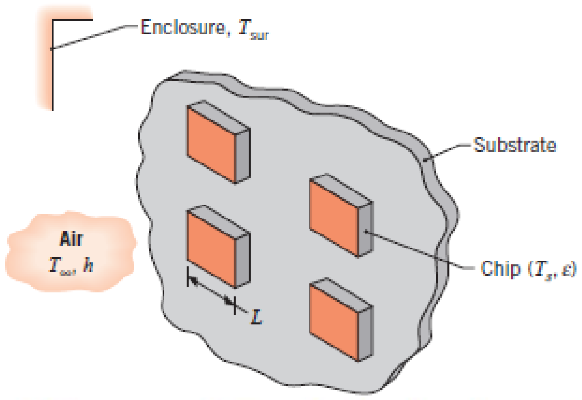
ace)

ound

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Example

1.40 Chips of width $L = 15$ mm on a side are mounted to a substrate that is installed in an enclosure whose walls and air are maintained at a temperature of $T_{sur} = 25°C$. The chips have an emissivity of $\varepsilon = 0.60$ and a maximum allowable temperature of $T_s = 85°C$.

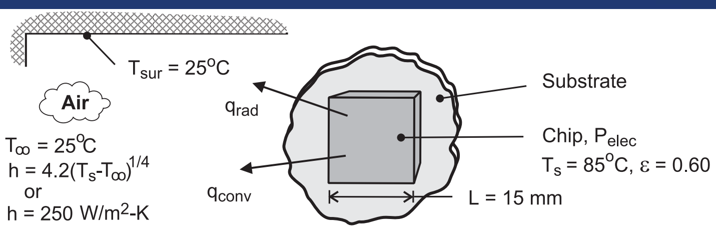


(a) If heat is rejected from the chips by radiation and natural convection, what is the maximum operating power of each chip? The convection coefficient depends on the chip-to-air temperature difference and may be approximated as $h = C(T_s - T_\infty)^{1/4}$, where $C = 4.2\ W/m^2 \cdot K^{5/4}$.

(b) If a fan is used to maintain airflow through the enclosure and heat transfer is by forced convection, with $h = 250\ W/m^2 \cdot K$, what is the maximum operating power?

Example cont.

Schematic:



Example cont.

THE SURFACE ENERGY BALANCE

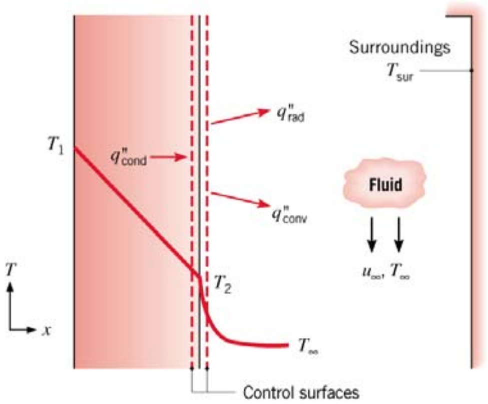
A special case for which no volume or mass is encompassed by the control surface.

Conservation Energy (Instant in Time):

$$\dot{E}_{in} - \dot{E}_{out} = 0$$ Applies for steady-state and transient conditions. **(1.12)**

- With no mass and volume, energy storage and generation are not pertinent to the energy balance, even if they occur in the medium bounded by the surface.

Consider surface of wall with heat transfer by conduction, convection and radiation.



$$q''_{cond} - q''_{conv} - q''_{rad} = 0$$

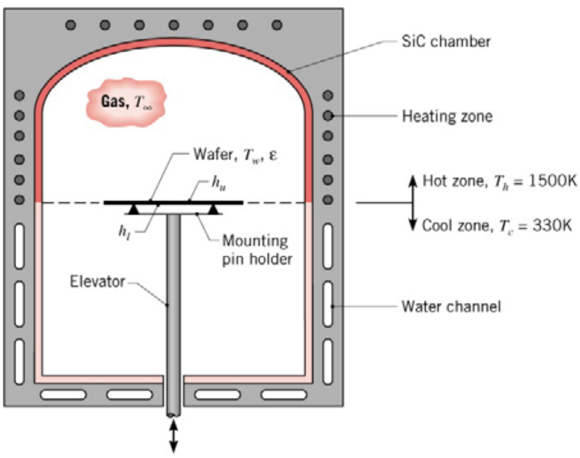
$$k\frac{T_1 - T_s}{L} = h(T_s - T_\infty) + \varepsilon\sigma(T_s^4 - T_{sur}^4)$$

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

METHODOLOGY OF FIRST LAW ANALYSIS

- On a schematic of the system, represent the control surface by dashed line(s).
- Choose the appropriate time basis.
- Identify relevant energy transport, generation and/or storage termsby labeled arrows on the schematic.
- Write the governing form of the Conservation of Energy requirement.
- Substitute appropriate expressions for terms of the energy equation.
- Solve for the unknown quantity.

Example



1.57 A furnace for processing semiconductor materials is formed by a silicon carbide chamber that is zone-heated on the top section and cooled on the lower section. With the elevator in the lowest position, a robot arm inserts the silicon wafer on the mounting pins. In a production operation, the wafer is rapidly moved toward the hot zone to achieve the temperature-time history required for the process recipe. In this position, the top and bottom surfaces of the wafer exchange radiation with the hot and cool zones, respectively, of the chamber. The zone temperatures are $T_h = 1500$ K and $T_c = 330$ K, and the emissivity and thickness of the wafer are $\varepsilon = 0.65$ and $d = 0.78$ mm, respectively. With the ambient gas at $T_\infty = 700$ K, convection coefficients at the upper and lower surfaces of the wafer are 8 and 4 $W/m^2 \cdot K$, respectively. The silicon wafer has a density of 2700 kg/m^3 and a specific heat of 875 $J/kg \cdot K$.

(a) For an initial condition corresponding to a wafer temperature of $T_{w,i} = 300$ K and the position of the wafer shown schematically, determine the corresponding time rate of change of the wafer temperature, $(dT_w/dt)_i$.

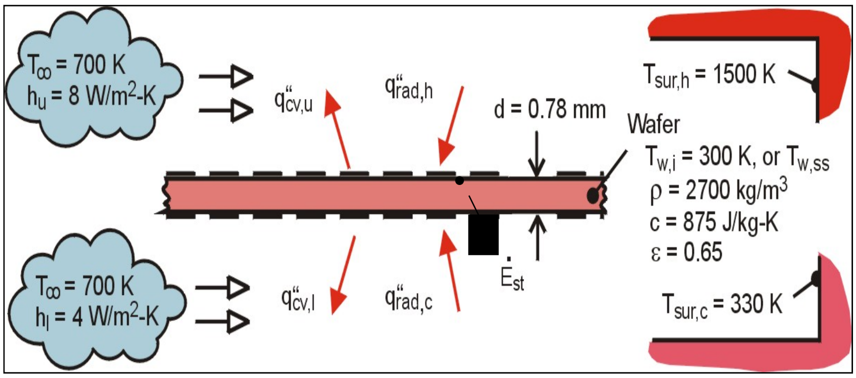
(b) Determine the steady-state temperature reached by the wafer if it remains in this position. How significant is convection heat transfer for this situation? Sketch how you would expect the wafer temperature to vary as a function of vertical distance.

- Process Heat Transfer

KNOWN: Silicon wafer positioned in furnace with top and bottom surfaces exposed to hot and cool zones, respectively.

FIND: (a) Initial rate of change of the wafer temperature corresponding to the wafer temperature $T_{w,i} = 300\,K$, and (b) Steady-state temperature reached if the wafer remains in this position. How significant is convection for this situation? Sketch how you'd expect the wafer temperature to vary as a function of vertical distance.

SCHEMATIC:



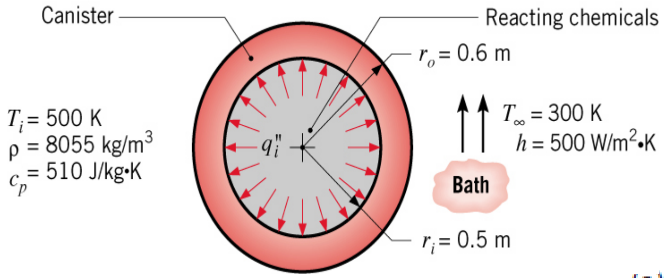
Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Example

1.64 A spherical, stainless steel (AISI 302) canister is used to store reacting chemicals that provide for a uniform heat flux q_i'' to its inner surface. The canister is suddenly submerged in a liquid bath of temperature $T_\infty < T_i$, where T_i is the initial temperature of the canister wall.



(a) Assuming negligible temperature gradients in the canister wall and a constant heat flux q_i'', develop an equation that governs the variation of the wall temperature with time during the transient process. What is the initial rate of change of the wall temperature if $q_i'' = 10^5$ W/m^2?

(b) What is the steady-state temperature of the wall?

SCHEMATIC: