Lecture 33 (Walker 16.4-6,17.1)

Heat Transfer
Ideal Gas & Ideal Gas Law

Dec. *4, 2009*

Quiz (Chaps. 14 & 16) on Mon. Dec. 7
(14.3, 14.9, 16.6 not covered)

Heat Transfer - Methods

- **Conduction - Thermal kinetic energy passed from particle-to-particle along a length of material.**
- **Convection - Thermal energy carried by moving fluid.**
- **Radiation - Thermal energy carried by electromagnetic waves.**

Heat Transfer: Conduction

The insulation value of building materials is given in terms of thermal resistance *R*–values rather than thermal conductivity:

$$R = \frac{l}{k}$$

Here, *l* is the thickness of the material.

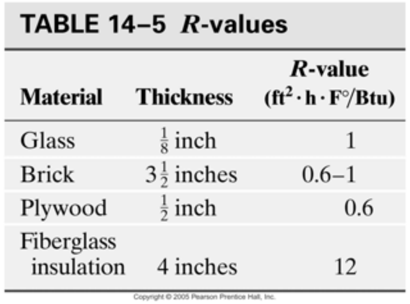


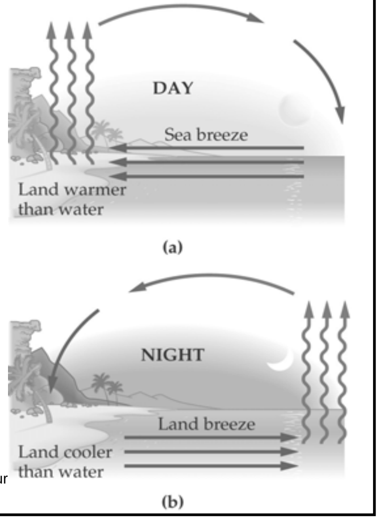
TABLE 14–5 *R*-values

Material	Thickness	*R*-value ($ft^2 \cdot h \cdot F°/Btu$)
Glass	$\frac{1}{8}$ inch	1
Brick	$3\frac{1}{2}$ inches	0.6–1
Plywood	$\frac{1}{2}$ inch	0.6
Fiberglass insulation	4 inches	12

Convection

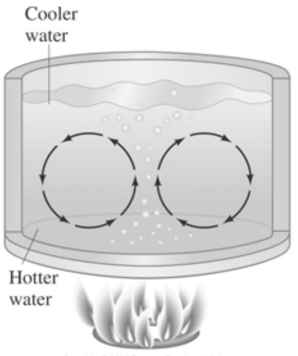
Convection is flow of fluid due to difference in temperatures, such as warm air rising. Fluid "carries" heat with it as it moves.

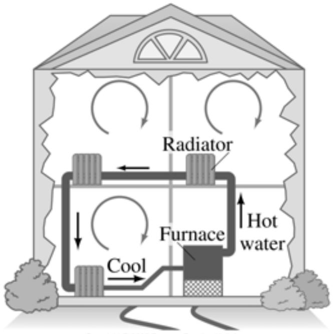
"Natural" convection: Warm fluid will rise because it is less dense then cold fluid.



Heat Transfer: Convection

Convection occurs when heat flows by the mass movement of molecules from one place to another. It may be natural or forced (fans); both these examples are natural convection.





Heat Transfer: Convection

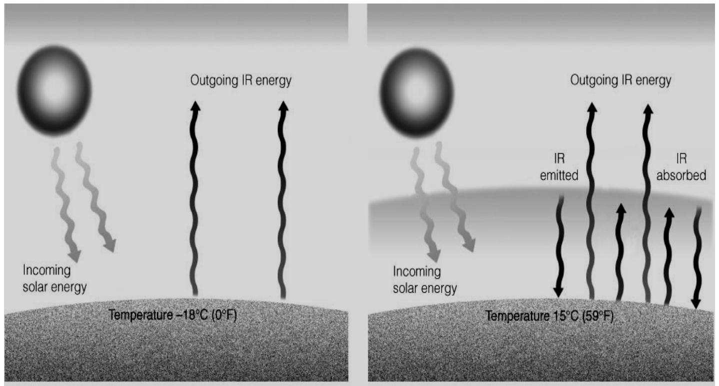
Many home heating systems are forced hot-air systems; these have a fan that blows the air out of registers, rather than relying completely on natural convection.

Our body temperature is regulated by the blood; it runs close to the surface of the skin and transfers heat. Once it reaches the surface of the skin, the heat is released through convection, evaporation, and radiation, along with a slight bit of conduction. (In water, there is much more conduction.)

Radiation

All objects give off energy in the form of radiation, as electromagnetic waves – infrared, visible light, ultraviolet – which, unlike conduction and convection, can transport heat through a vacuum.

Objects that are hot enough will glow visibly – first red, then yellow, white, and blue as temperature increases. Objects at body temperature radiate in the infrared, and can be seen with night vision binoculars.



(a) Without greenhouse effect

(b) With greenhouse effect

Radiation

The amount of energy radiated per second by an object due to its temperature is proportional to its surface area and also to the fourth (!) power of its temperature.

Radiated power also depends on emissivity e of the surface, which is a number between 0 and 1 that indicates how effective a radiator the object is.

A perfect radiator ("black body") would have e=1. A perfect reflector ("shiny" object) would not radiate at all; e=0.

Radiation

This behavior is contained in the Stefan-Boltzmann law:

Stefan-Boltzmann Law for Radiated Power, *P*

$$P = e\sigma A T^4$$

SI unit: W

Here, e is the emissivity, and σ is the Stefan-Boltzmann constant:

$$\sigma = 5.67 \times 10^{-8}\ \mathrm{W/(m^2 \cdot K^4)}$$

The temperature must be in Kelvin units!

Radiation

If you are sitting in a place that is too cold, your body radiates and loses to convection more heat than it is producing. You will start shivering and your metabolic rate will increase unless you put on clothing that has good insulation and/or low emissivity ("space blanket".)

Emissivity also determines how well a surface absorbs radiant energy.

e = 1 perfect absorber (perfect black body)

e = 0 perfect reflector (mirror)

An object at temperature T in surroundings of temperature T_s will both radiate and absorb power. The net radiated power is

$$P_{net} = e\sigma A(T^4 - T_s^4)$$

Example

- Person wants to "burn off" 400 Calories (1.7×10^6 J) by standing naked in ice cave at -10°C. How long will it take if cooling is by radiation only? Take e=0.9; A=1.5m^2; T = 37°C = 310K; Ts = -10°C = 263K

$$P_{net} = e\sigma A(T^4 - T_s^4)$$

$$=(0.9)(5.7\times10^{-8}\mathrm{W/m^2K^4})(1.5\mathrm{m^2})[(310\mathrm{K})^4-(263\mathrm{K})^4]$$

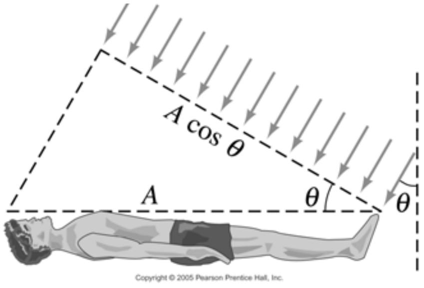
$$= 340\mathrm{W}$$

Q = Pt, so $t=1.7\times10^6\mathrm{J}/340\mathrm{W}= 4900\mathrm{s} = 1.4\mathrm{hr}$

Radiation

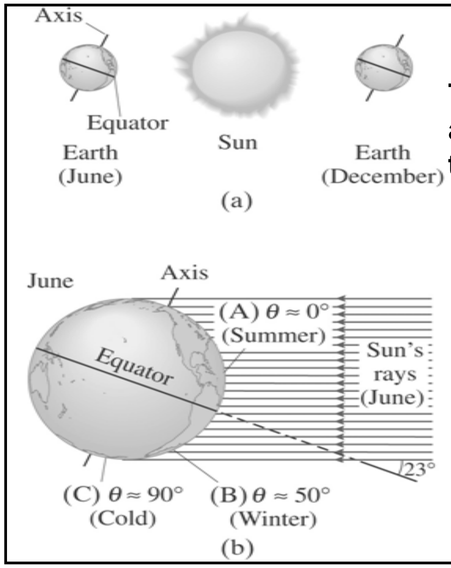
If you are in sunlight, Sun's radiation will warm you. The intensity of solar radiation is 1000 W/m^2. In general, you will not be perfectly perpendicular to the Sun's rays, and will absorb energy at the rate:

$$\frac{\Delta Q}{\Delta t} = \left(1000\ \mathrm{W/m^2}\right) e A \cos\theta$$



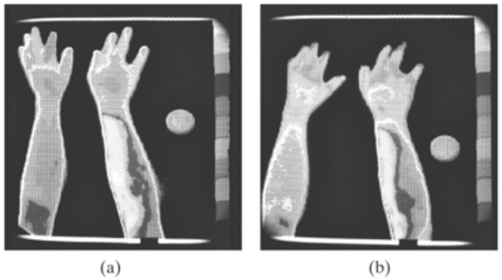
Seasons

This cos *θ* effect is also responsible for the seasons.



Heat Transfer: Radiation

Thermography – detailed measurement of radiation from the body – can be used in medical imaging. Warmer areas may be a sign of tumors or infection; cooler areas on the skin may be a sign of poor circulation.

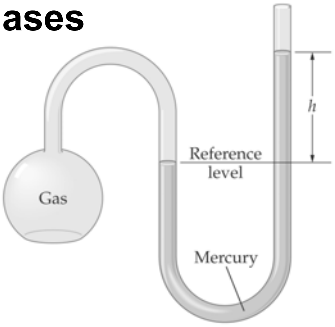

(a) (b)

Ideal Gases

Gases are the easiest state of matter to describe, as all ideal gases exhibit similar behavior.

An ideal gas is one that has low enough density, and is far enough away from condensing to liquid, that the <u>interactions between molecules can be ignored</u>.

Ideal Gases

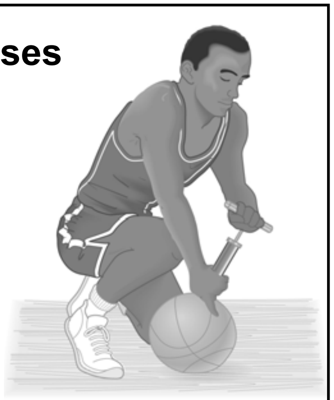


If the volume of an ideal gas is held constant, we find that the pressure increases with temperature:

$$P = (\text{constant})T$$

(fixed volume, V; fixed number of molecules, N)

Ideal Gases

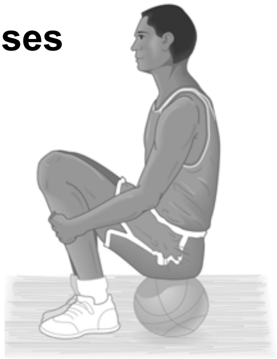


If the volume and temperature are kept constant, but more molecules N of gas are added (such as in inflating a tire or basketball), the pressure will increase:

$$P = (\text{constant})N$$

(fixed volume, V; fixed temperature, T)

Ideal Gases



Finally, if the temperature is constant and the volume decreases, the pressure increases:

$$P = \frac{(\text{constant})}{V}$$

(fixed number of molecules, N; fixed temperature, T)

Ideal Gases

Combining all three observations, we write

$$P = k\frac{NT}{V}$$

where *k* is called the Boltzmann constant:

Boltzmann Constant, *k*

$$k = 1.38 \times 10^{-23}\ \text{J/K}$$

SI unit: J/K

Ideal Gases

Rearranging gives us the equation of state for an ideal gas:

Equation of State for an Ideal Gas

$$PV = NkT$$

Instead of counting molecules, we can count moles. A mole is the amount of a substance that contains *Avogadro's number* N_A of molecules.

Avogadro's Number, N_A

$N_A = 6.022 \times 10^{23}$ molecules/mol

SI unit: mol^{-1}; the number of molecules is dimensionless

***n* moles of gas will contain nN_A molecules.**

Ideal Gases

Avogadro's number and the Boltzmann constant can be combined to form the universal gas constant and an alternative equation of state:

Universal Gas Constant, *R*

$R = N_A k = (6.022 \times 10^{23} \text{ molecules/mol})(1.38 \times 10^{-23} \text{ J/K})$

$= 8.31 \text{ J/(mol} \cdot \text{K)}$

SI unit: $\text{J/(mol} \cdot \text{K)}$

Equation of State for an Ideal Gas

$$PV = nRT$$

where n is the number of moles of gas present.

Problem Solving with the Ideal Gas Law

Useful facts and definitions:

- **Standard temperature and pressure (STP)**

$$T = 273\text{ K} \quad (0°\text{C})$$

$$P = 1.00\text{ atm} = 1.013 \times 10^5\text{ N/m}^2 = 101.3\text{ kPa}$$

- **Volume of 1 mol of an ideal gas at STP is 22.4 L**
- **If the amount of gas does not change:**

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

- **Always measure *T* in kelvins**
- ***P* must be the absolute pressure**

Ideal Gases

The atomic or molecular mass of a substance is the mass, in grams, of one mole of that substance. For example,

Helium: $M = 4.00260 \text{ g/mol}$

Copper: $M = 63.546 \text{ g/mol}$

Furthermore, the mass of an individual atom is given by the atomic mass divided by Avogadro's number:

$$m = \frac{M}{N_A}$$

Example

- We have 1 mole of ideal gas at a temperature of 40°C at atmospheric pressure (101 kPa). Volume?
- $T = 313K$
- $PV = nRT$ so $V = nRT/P$
  $V = (1\text{mol})(8.31\ \text{J/mol-K})(313\text{K})/(1.01\times10^5\text{Pa})$
  $= 2.58 \times 10^{-2}\ \text{m}^3 = 25.8$ liters

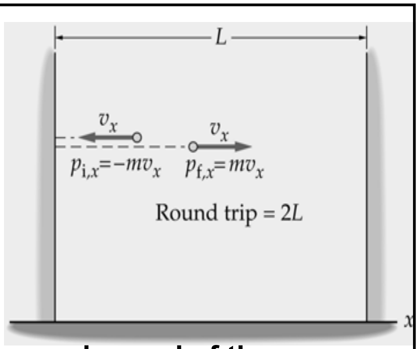
Kinetic Theory

Kinetic theory of gases relates microscopic quantities (position, velocity) to macroscopic ones (pressure, temperature). Assumptions:

- **N identical molecules of mass m are inside a container of volume V; each acts as a point particle.**
- **Molecules move randomly and always obey Newton's laws.**
- **Collisions with other molecules and with the walls are elastic.**

Kinetic Theory

Pressure is the result of collisions between gas molecules and walls of container.



It depends on the mass and speed of the molecules, and on the container size:

$$P = \frac{F}{A} = \frac{(mv_x^2/L)}{L^2} = \frac{mv_x^2}{L^3} = \frac{mv_x^2}{V}$$

End of Lecture 33

- For Monday, Dec. 7, read Walker 17.2, 17.4-5.
- Homework Assignment 16b is due at 11:00 PM on Monday, Dec. 7.
- Quiz (Chaps. 14 & 16) on Mon. Dec. 7